NASA TECHNICAL MEMORANDUM

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LaRC DESIGN ANALYSIS REPORT

FOR

NATIONAL TRANSONIC FACILITY

FOR

9% NICKEL TUNNEL SHELL

FINITE DIFFERENCE ANALYSIS OF CONE/CYLINDER JUNCTION

VOL. 1

BY

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Formal Documentation of Design Analyses to Obtain Code Approval of Fabricated National Transonic Facility

16. Abstract This report contains the results of extensive computer (finite element, finite difference and numerical integration), thermal, fatigue, and special analyses of critical portions of a large pressurized, cryogenic wind tunnel (National Transonic Facility). The computer models, loading and boundary conditions are described. Graphic capability was used to display model geometry, section properties, and stress results. A stress criteria is presented for evaluation of the results of the analyses. Thermal analyses were performed for major critical and typical areas. Fatigue analyses of the entire tunnel circuit is presented.

The major computer codes utilized are: SPAR - developed by Engineering Information Systems, Inc. under NASA Contracts NAS8-30536 and NAS1-13977; SALORS - developed by Langley Research Center and described in NASA TN D-7179; and SRA - developed by Structures Research Associates under NASA Contract NAS1-10091; "A General Transient Heat-Transfer Computer Program for Thermally Thick Walls" developed by Langley Research Center and described in NASA TM X-2058.

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NTF TUNNEL SHELL

NASA LaRC

FINITE DIFFERENCE ANALYSIS
OF
CONE/CYLINDER JUNCTION

9% NICKEL

SEPTEMBER 1976

VOLUME 1

LaRC CALCULATIONS

FOR THE

NATIONAL TRANSONIC FACILITY

TUNNEL SHELL

DATE: SEPTEMBER, 1976

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This report is one volume of a Design Analysis Report prepared by LaRC on portions of the pressure shell for the National Transonic Facility. This report is to be used in conjunction with reports prepared under NASA Contract NAS1-13535(c) by the Ralph M. Parsons Company (Job Number 5409-3 dated September 1976) and Fluidyne Engineering Corporation (Job Number 1060 dated September 1976). The volumes prepared by LaRC are listed below:

1. Finite Difference Analysis of Cone/Cylinder (9% Ni), Vol. 1, NASA TM X73956-1.

2. Finite Element Analysis of Corners #3 and #4 (9% Ni), Vol. 2, NASA TM X73956-2.

3. Finite Element Analysis of Plenum Region Including Side Access Reinforcement, Side Access Door and Angle of Attack Penetration (9% Ni), Vol. 3, NASA TM X73956-3.

4. Thermal Analysis (9% Ni), Vol. 4, NASA TM X73956-4.

5. Finite Element and Numerical Integration Analyses of the Bulkhead Region (9% Ni), Vol. 5, NASA TM X73956-5.

6. Fatigue Analysis (9% Ni), Vol. 6, NASA TM X73956-6.

7. Special Studies (9% Ni), Vol. 7, NASA TM X73956-7.

NTF DESIGN CRITERIA FOR 9% NICKEL

GENERAL

THE DESIGN OF THE PRESSURE SHELL REFLECTED IN THIS REPORT SATISFIES THE DESIGN REQUIREMENTS OF THE ASME BOILER AND PRESSURE VESSEL CODE, SECTION VIII, DIVISION 1. SINCE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN, ADDITIONAL ANALYSES WERE PERFORMED IN AREAS HAVING COMPLEX CONFIGURATIONS SUCH AS THE CONE CYLINDER JUNCTIONS, THE GATE VALVE BULKHEADS, THE BULKHEAD-SHELL ATTACHMENTS, THE PLENUM ACCESS DOORS AND REINFORCEMENT AREAS, THE ELLIPTICAL CORNER SECTIONS, AND THE FIXED REGION (RING S8) OF THE TUNNEL. THE DIVISION 1 DESIGN CALCULATIONS, THE ADDITIONAL ANALYSES AND THE CRITERIA FOR EVALUATION OF THE RESULTS OF THE ADDITIONAL ANALYSES TO ENSURE COMPLIANCE WITH THE INTENT OF DIVISION 1 REQUIREMENTS ARE CONTAINED IN THE TEXT OF THIS REPORT. THE DESIGN ANALYSES AND ASSOCIATED CRITERIA CONSIDERED BOTH THE OPERATING AND HYDROSTATIC TEST CONDITIONS.

IN CONJUNCTION WITH THE DESIGN, A DETAILED FATIGUE ANALYSIS OF THE PRESSURE SHELL WAS ALSO PERFORMED UTILIZING THE METHODS OF THE ASME CODE, SECTION VIII, DIVISION 2.

MATERIAL

THE PRESSURE SHELL MATERIAL SHALL BE ASME, SA-553-1 FOR PLATE AND SA-522 FOR FORGINGS. THE MATERIAL PROPERTIES AT TEMPERATURES EQUAL TO OR BELOW 150°F ARE AS FOLLOWS:

(A) PLATE, 2.0 INCHES OR THINNER

YIELD = 85.0 KSI
ULTIMATE = 100 KSI

(B) WELDS (AUTOMATIC AND SEMIAUTOMATIC)

YIELD = 52.5 KSI
ULTIMATE = 95.0 KSI

(C) WELDS (HAND)

YIELD = 58.5 KSI
ULTIMATE = 95.0 KSI

OPERATING, DESIGN AND TEST CONDITIONS

THE OPERATING, DESIGN AND TEST CONDITIONS FOR THE TUNNEL PRESSURE SHELL AND ASSOCIATED SYSTEMS AND ELEMENTS ARE SUMMARIZED BELOW:

1. OPERATING MEDIUM

   ANY MIXTURE OF AIR AND NITROGEN

2. DESIGN TEMPERATURE RANGE

   MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT, EXCEPT IN THE REGION OF THE PLENUM BULKHEADS AND GATE VALVES INSIDE A 23-FOOT, 4-INCH DIAMETER, FOR WHICH THE TEMPERATURE RANGE IS MINUS 320 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT.

3. PRESSURE RANGE

	TUNNEL CONFIGURATION	OPERATING PRESSURE RANGE, PSIA	DESIGN PRESSURES PSID
A.	CONDITION I - PLENUM ISOLATION GATES OPEN AND TUNNEL OPERATING:		
	TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	PLENUM (PLENUM PRESSURE IS LIMITED TO .4 TO 1 TIMES THE REMAINDER OF THE TUNNEL CIRCUIT	3.3 to 130	A. 15 EXTERNAL B. 119 INTERNAL
	BULKHEAD		56 (EXTERNAL TO PLENUM)
B.	CONDITION II - PLENUM ISOLATION GATES OPEN AND TUNNEL SHUTDOWN:		
	ENTIRE TUNNEL CIRCUIT	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	BULKHEAD		0

C. CONDITION III - PLENUM ISOLATION GATES AND ACCESS DOORS CLOSED:

TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM (PLENUM OPERATING PRESSURE CAN EXCEED THE PRESSURE IN THE REMAINDER OF THE TUNNEL CIRCUIT BY 24 PSI, BUT DOES NOT EXCEED THE 130 PSIA MAXIMUM OPERATING PRESSURE)	0 to 130	A. 15 EXTERNAL B. 119 INTERNAL
BULKHEAD		A. 25 (INTERNAL TO PLENUM) B. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *C. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

D. CONDITION IV - PLENUM ISOLATION GATES CLOSED AND ACCESS DOORS OPEN:

TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM	14.7	0
BULKHEAD		A. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *B. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

4. HYDROSTATIC TEST DESIGN CONDITIONS

THE PRESSURE SHELL WAS DESIGNED FOR HYDROSTATIC TEST IN ACCORDANCE WITH THE REQUIREMENTS OF THE ASME CODE, SECTION VIII, DIVISION 1. THE TEST PRESSURES SHALL BE AS FOLLOWS. PRESSURE SHELL TEMPERATURE SHALL BE EQUAL TO OR BELOW 100°F DURING HYDROSTATIC TESTS.

CONDITION (1) - MAXIMUM INTERNAL PRESSURE CONDITION FOR THE ENTIRE TUNNEL CIRCUIT

PH_1 = 1.5 (119) + HYDROSTATIC HEAD
= 178.5 PSI + HYDROSTATIC HEAD

CONDITION (2) - MAXIMUM DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

PH_2 = 1.5 (119) + HYDROSTATIC HEAD
= 178.5 + HYDROSTATIC HEAD

PH_2* = 1.5 (111.5) $\left(\frac{23.7}{22.2}\right)$ + HYDROSTATIC HEAD

= 178.5 + HYDROSTATIC HEAD

*TUNNEL OPERATION LIMITATIONS PRECLUDE PRESSURE DIFFERENTIALS ACROSS BULKHEADS IN EXCESS OF 110.5 PSI FOR BULKHEAD AND GATE TEMPERATURES IN EXCESS OF 150°F.

CONDITION (3) - MAXIMUM REVERSE DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

PH_3 = 1.5 (25) = 37.5 PSI

THE PRESSURE SHELL EXCEPT FOR THE PLENUM SHALL BE PRESSURIZED TO 141 PSIG. THE PLENUM SHALL BE PRESSURIZED TO 178.5 PSIG.

PRESSURE SHELL STRESS EVALUATION CRITERIA

THIS CRITERIA ESTABLISHES THE BASIS FOR ANALYSIS AND DESIGN OF THE PRESSURE SHELL SO IT WILL MEET OR EXCEED ALL OF THE REQUIREMENTS OF SECTION VIII, DIVISION 1 OF THE ASME BOILER AND PRESSURE VESSEL CODE AND CAN BE STAMPED WITH A DIVISION 1 "U" STAMP.

1. SECTION VIII, DIVISION 1, DIRECT APPLICATION

A. THE MAXIMUM ALLOWABLE STRESS (S)

S = 23.7 KSI (-320°F TO +150°F)

S = 22.2 KSI (-320°F TO +200°F)

(B) PRIMARY BENDING PLUS PRIMARY MEMBRANE STRESSES

THE LOCAL MEMBRANE STRESSES ARE NOT GENERALLY CONSIDERED IN SECTION VIII, DIVISION 1 DESIGNS. HOWEVER, FOR THE PURPOSE OF DESIGNING LOCAL REINFORCEMENT AT BRACKETS, RINGS OR PENETRATIONS NOT COVERED BY DESIGN BASED ON STRESS ANALYSIS, THE LOCAL SHELL MEMBRANE STRESS SHALL BE:

$$P_b + P_m \leq 1.5\ SE$$

NOTE: E IS JOINT EFFICIENCY

2. IN REGIONS OF THE PRESSURE SHELL WHERE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN (REF. U-2(g)), ADDITIONAL ANALYSES WERE PERFORMED UTILIZING THE GUIDELINES OF THE ASME CODE, SECTION VIII, DIVISION 2, APPENDIX 4, "DESIGN BASED ON STRESS ANALYSIS." THE BASIC STRESS CRITERIA FOR DIVISION 2 IS REPRESENTED IN FIGURE 4-130.1 AND RESTATED BELOW INDICATING ANY MODIFICATIONS OR EXCESS REQUIREMENTS APPLIED TO IT TO REMAIN WITHIN THE INTENT OF DIVISION 1 AND TO OBTAIN A DIVISION 1 STAMP.

A. GENERAL PRINCIPAL MEMBRANE STRESS

MAXIMUM ALLOWABLE STRESS

S = 23.7 KSI (-320°F TO +150°F)

S = 22.2 KSI (-320°F TO +200°F)

MAXIMUM ALLOWABLE STRESS INTENSITY

S_m = 31.7 KSI (-320°F TO +200°F)

B. PRIMARY GENERAL MEMBRANE STRESS INTENSITY

$$P_m \leq S_m$$

AND IN ORDER TO COMPLY WITH DIVISION 1, THE MAXIMUM PRINCIPAL MEMBRANE STRESS MUST BE:

$$P_m^* \leq S$$

NOTE: THE * IS USED TO DENOTE THAT MAXIMUM PRINCIPAL STRESSES ARE TO BE COMPUTED FOR THE GIVEN LOADING CONDITION. THE INTENT IS TO DETERMINE THE STRESSES WHICH REPRESENT THE HOOP STRESSES AND MERIDIONAL STRESSES WHICH ARE THE STRESSES USED IN DIVISION 1 COMPUTATIONS.

C. DESIGN LOADS, PRIMARY LOCAL MEMBRANE STRESS INTENSITY

$$P_L \leq 1.5\ S_m$$

NOTE: LOCAL MEMBRANE STRESS INTENSITY IS DEFINED IN ACCORDANCE WITH DIVISION 2, APPENDIX 4-112(i). THE TOTAL MERIDIONAL LENGTH IS CONSIDERED TO BE 1.0 $\sqrt{RT}$.

D. DESIGN LOADS, PRIMARY LOCAL MEMBRANE PLUS PRIMARY BENDING STRESS INTENSITY

$$P_L + P_b \leq 1.5\ S_m$$

E. OPERATING LOADS, PRIMARY PLUS SECONDARY STRESS INTENSITY

$$P_L + P_b + Q \leq 3\ S_m$$

F. COMMENT

BECAUSE OF THE LOW YIELD STRENGTH EXPECTED AT THE WELDS AS COMPARED TO THE YIELD STRENGTH OF THE PLATE, STRESS INTENSITIES COMPUTED IN (A), (B), (C), (D), OR (E) SHALL NOT EXCEED THE YIELD STRENGTH OF THE MATERIAL AT EITHER WELD OR PLATE LOCATIONS.

3. A FATIGUE ANALYSIS WAS CONDUCTED IN ACCORDANCE WITH SECTION VIII, DIVISION 2 WITHOUT MODIFICATION.

4. HYDROSTATIC TEST CONDITION DESIGN CONSIDERATIONS

A. PRESSURE SHELL

IN ACCORDANCE WITH DIVISION 1 OF THE ASME CODE, DESIGN ANALYSIS OF THE PRESSURE SHELL FOR THE HYDROSTATIC TEST CONDITION IS NOT REQUIRED. HOWEVER, IN ORDER TO PROVIDE A SATISFACTORY ENGINEERING DESIGN FOR THE PRESSURE SHELL THE FOLLOWING CRITERIA WAS USED:

(a) THE MAXIMUM GENERAL MEMBRANE STRESS PERPENDICULAR TO A WELD LINE WAS LIMITED TO THE LESSER OF:

$$P_m{}^* \leq 0.8 \text{ WELD YIELD STRESS}$$

OR

$$P_m{}^* \leq 0.5 \text{ WELD ULTIMATE STRESS}$$

(b) THE GENERAL PRINCIPAL MEMBRANE STRESS IN THE PLATE (NOT AT A WELD) WAS LIMITED TO THE LESSER OF:

P_m * $\leq$ 0.8 PLATE YIELD STRESS

P_m * $\leq$ 0.5 PLATE ULTIMATE STRESS

(*) THE STRESSES SATISFYING THIS CRITERIA ARE BASED ON MAXIMUM MEMBRANE STRESSES RATHER THAN INTENSITY CRITERIA.

Vol 1

Finite Difference Analyses of Cone / cylinder Junctions

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Part 2

Part 3

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9% Ni

Part 1

Reference Drawing No 944383 + 944390

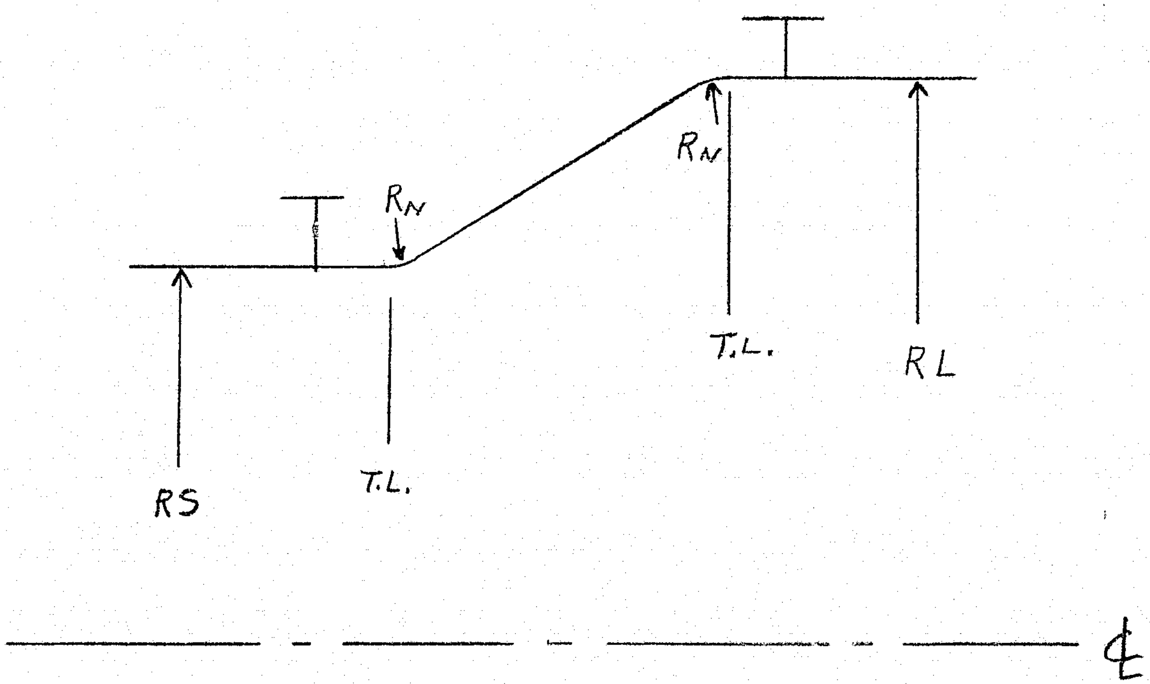
The cone / cylinder junctions were analyzed utilizing a shell of revolution computer code.

Computer Code

SALORS – Structural Analysis of Layered Orthotropic Ring-Stiffened Shell-of-Revolution – is a finite-difference code

Reference NASA TN D-7179

A typical cone / cylinder is shown below.



Loading

Internal pressure = 119 psig for Design condition

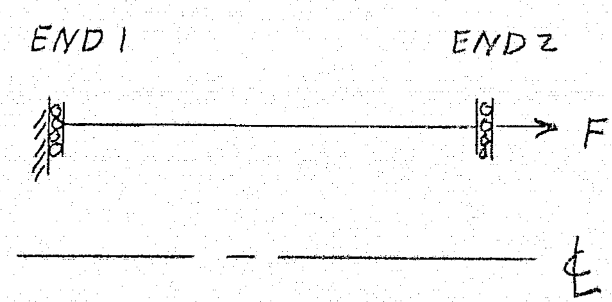
Internal pressure = 1.5(119) + water head for Hydro test condition

All pressure loadings remain normal to the deformed surface

Boundary Conditions

Symmetric B. C. were applied to each end of the model

End 1 was fixed in the axial direction. A boundary force of $\frac{1}{2}PR$ (lb/in of. circ.) was applied to end 2



R1 to S2

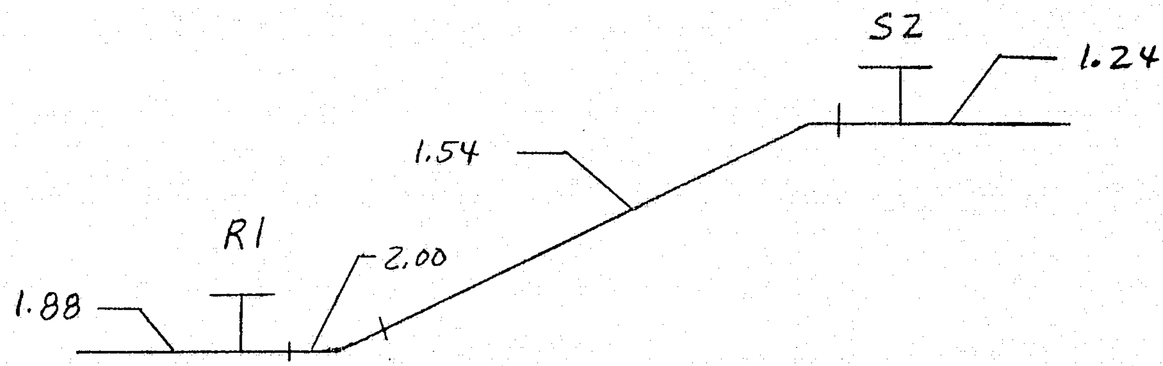


Fig. 1 Computer plot of geometry

Fig 2 Average net-section hoop Stress
P= 119 psi

Fig 3 Inside surface stress
longitudinal + Hoop
P= 119 psi

Fig 4 Outside surface stress
longitudinal + Hoop
P= 119 psi

Fig 5 Radial displacement

Knuckle region at small dia cylinder

This model did NOT include the influence from CORNER #4 (elliptical ring R1). This region was considered in detail in the analyses of CORNER #4. See corner #4 (Vol 4) analyses of this region

Knuckle region at large dia cylinder

Membrane Stress (Stress intensity)

Primary local membrane stress intensity
(see Fig 2, 3 & 4)

$\sigma_1 = -26.2$ KSI

$\sigma_2 = \dfrac{-18.5 + 35.5}{2} = 8.5$ KSI

$\sigma_3 = -\dfrac{.119}{2} = -.06$ KSI

$S_{12} = \sigma_1 - \sigma_2 = -26.2 - 8.5 = -34.7$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 8.5 - (-.06) = 8.56$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.06 - (-26.2) = 26.18$ KSI

$P_L = |-34.7| = 34.7$ KSI

$P_L = 34.7$ KSI $< 1.5\,S_m = 1.5(31.7) = 47.55$ KSI

O.K.

The meridional length at a stress intensity of 1.1 Sm ($1.1 \times 31.7 = 34.87$ KSI) is 0. The peak stress intensity is less than 1.1 Sm

$$0 < \sqrt{RT} = \sqrt{(41')(12)(1.54)} = 27.5 \quad \text{O.K.}$$

∴ The stress intensity in this region is a local membrane stress intensity

General Membrane Stress Intensity

$$\sigma_1 = 22.7 \text{ KSI}$$

$$\sigma_2 = \frac{18.0 + 3}{2} = 10.5 \text{ KSI}$$

$$\sigma_3 = -\frac{.119}{2} = -.06 \text{ KSI}$$

$$S_{12} = \sigma_1 - \sigma_2 = 22.7 - 10.5 = 12.2 \text{ KSI}$$

$$S_{23} = \sigma_2 - \sigma_3 = 10.5 - (-.06) = 10.56 \text{ KSI}$$

$$S_{31} = -.06 - 22.7 = -22.76 \text{ KSI}$$

$$P_m = |-22.76| = 22.76 \text{ KSI}$$

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R1 to S2

$P_m = 22.76 < S_m = 31.7$ KSI o.k.

General principal membrane stress

$\sigma = 22.7$ KSI on cone

$\sigma = 23.7$ KSI on cylinder

$\sigma \leq S$

$23.7 \leq S = 23.7$ o.k.

The membrane stress (intensity), meets the stress evaluation criteria

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 35.5$ KSI

$\sigma_2 = -16.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 35.5 - (-16.0) = 51.5$ KSI

$S_{23} = \sigma_1 - \sigma_2 = -16.0 - .119 = -16.12$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.119 - 35.5 = -35.62$ KSI

$S_1 = |51.5| = 51.5$ KSI

$P_L + P_b + Q \leq \sigma_{yp}$ (plate or weld)

$P_L + P_b + Q = 51.5 < 52.5 \quad \therefore$ O.K.

Outside Surface

$\sigma_1 = -31$ KSI

$\sigma_2 = -17$ KSI

$\sigma_3 = 0$

$S_{12} = \sigma_1 - \sigma_2 = -31 - (-17) = -14$ KSI

$S_{23} = \sigma_2 - \sigma_3 = -17 - 0 = -17$ KSI

$S_{31} = \sigma_3 - \sigma_1 = 0 - 31 = -31$ KSI

$S = |-31| = 31$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (plate or weld)

$P_L + P_b + Q = 31 < 52.5$ KSI $\therefore$ OK.

The primary plus secondary stress intensity meets the stress evaluation criteria

Hydro Test conditions

The hydro test pressure was assumed to be the max. pressure at the bottom of the tunnel for the region under consideration.

Knuckle region at the small dia cyl.

See Corner #4 analyses

Knuckle region at the large dia cylinder

$$P_H = 1.5(119) + \text{water head}$$

$$P_H = 1.5(119) + 62.4 \frac{lb}{ft^3} \times \frac{1\ ft^2}{144\ in^2} \left[41 \right]$$

$$P_H = 178.5 + 17.77$$

$$P_H = 196.27 \text{ psi}$$

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R1 to S2

Fig 6 Average net-section hoop stress P= 193 psi

Fig 7 Inside surface stress longitudinal + hoop
P= 193 psi

Fig 8 Outside surface stress longitudinal + hoop
P= 193 psi

For the region of knuckle at the large dia., the stress at hydro. test condition is

$$S_{Hx} = \frac{196.3}{193.0} \left(S_{H_{193}} \right)$$

Max membrane (see Fig 6)

$$S_{Hx} = \frac{196.3}{193.0} (-37.5) = -38.14 \text{ ksi}$$

$$S_{Hx} = \frac{196.3}{193} (39) = 39.67 \text{ ksi}$$

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RI to S2

σ_{yp} (weld - auto) = 52.5 KSI

σ_{ut} (weld) = 95.0 KSI

smaller of

$P_m \leq 0.8\ (52.5) = 42.0$ KSI

or

$P_m \leq 0.5\ (95) = 47.5$ KSI

$39.67 < 42.0$ KSI

This region satisfies the stress evaluation criteria for hydro test.

S3 to R3

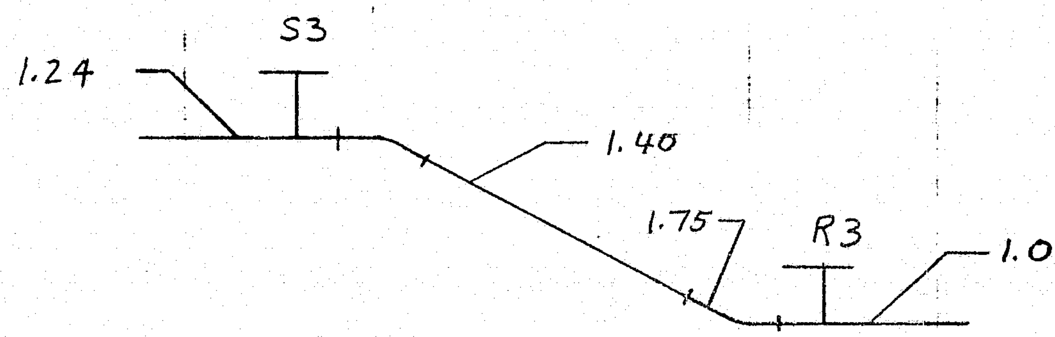

Fig 9	Computer plot of geometry
Fig 10	Average net-section hoop stress P= 119 psi
Fig 11	Inside surface stress longitudinal & hoop P= 119 psi
Fig 12	Outside surface stress longitudinal & hoop P= 119 psi
Fig 13	Radial displacement P= 119 psi

Knuckle region at the small dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity
see Fig 10, 11 + 12

$\sigma_1 = 31.8$ KSI

$\sigma_2 = \frac{24 + (-12)}{2} = 6$ KSI

$\sigma_3 = -\frac{.119}{2} = -.06$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 31.8 - 6 = 26.8$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 6 - (-.06) = 6.06$ KSI

$S_{31} = -.06 - 31.8 = -32.4$ KSI

$S_{..} = |-32.4| = 32.4$ KSI

$P_L = 32.4$ KSI $< 1.5 S_m = 47.55$ KSI O.K.

S3 to R3

The meridional length at a stress intensity of 1.1 Sm ($1.1 \times 31.7 = 34.87$ KSI) is 0. The peak stress intensity is less than 1.1 Sm

$$0 < \sqrt{RT} = \sqrt{(14.06')(12)(1.75)} = 17.18'' \quad \text{O.K.}$$

∴ The stress intensity in this region is a local membrane stress intensity

General Membrane Stress Intensity

$$\sigma_1 = 20.8 \text{ KSI}$$

$$\sigma_2 = \frac{9 + 11}{2} = 10 \text{ KSI}$$

$$\sigma_3 = -\frac{.119}{2} = -.06 \text{ KSI}$$

BY	DATE	SUBJECT	SHEET NO. 17 OF
CHKD. BY	DATE		JOB NO.
		S3 to R3	

$S_{12} = \sigma_1 - \sigma_2 = 20.8 - 10 = 18.8$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 10.0 - (-.06) = 10.06$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.06 - 20.8 = -20.86$ KSI

$S = |-20.86| = 20.86$ KSI

$P_m = 20.86 < S_m = 31.7$ KSI O.K.

General principal membrane stress

$S = 20.8$ KSI cyl.

$20.8 < S = 23.7$ KSI O.K.

The membrane stress (intensity) meets the stress evaluation criteria.

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 26.2$ KSI

$\sigma_2 = -12.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 26.2 - (-12.0) = 38.2$ KSI

$S_{23} = \sigma_2 - \sigma_3 = -12.0 - (-.12) = -12.12$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.12 - 26.2 = -26.32$ KSI

$S_I = |38.2| = 38.2$ KSI

$P_L + P_b + Q < \sigma_{yp}$ (weld or plate)

$P_L + P_b + Q = 38.2 < 52.5$ KSI (auto weld)

O.K.

BY ______ DATE ______ SUBJECT ______ SHEET NO. 19 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______
S3 to R3

Outside Surface

$\sigma_1 = 37.0$ KSI

$\sigma_2 = 24.0$ KSI

$\sigma_3 = 0$

$S_{12} = \sigma_1 - \sigma_2 = 37.0 - 24.0 = 13.$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 24.0 - 0 = 24.0$ KSI

$S_{31} = \sigma_3 - \sigma_1 = 0 - 37.0 = -37.0$ KSI

$S = |-37.0| = 37.0$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (weld)

$P_L + P_b + Q = 37.0 < 52.5$ KSI (auto weld) O.K.

$\therefore$ The primary plus secondary stress intensity meets the stress evaluation criteria.

Knuckle region at the large dia. cylinder

Membrane stress (intensity)

Primary local membrane stress intensity
see Fig 10, 11 & 12

$\sigma_1 = -17.5$ KSI

$\sigma_2 = \dfrac{-20 + 41.5}{2} = 10.75$ KSI

$\sigma_3 = -\dfrac{.119}{2} = -.06$ KSI

$S_{12} = \sigma_1 - \sigma_2 = -17.5 + 10.75 = 6.75$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 10.75 - (-.06) = 11.35$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.06 - (-17.5) = 17.44$ KSI

$S = |17.44| = 17.44$ KSI

$P_m = 17.44 < S_m = 31.7$ KSI

Since the stress intensity is < Sm, the stress intensity meets the criteria for the general membrane stress intensity.

General Membrane Stress

S = - 17.5 KSI
S = 23.7 KSI

23.7 ≤ 23.7 KSI O.K.

∴ The membrane stress (intensity) meets the stress evaluation criteria.

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 42.0$ KSI

$\sigma_2 = 9.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 42.0 - 9.0 = 33$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 9.0 - .12 = 8.88$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.12 - 42 = -42.12$ KSI

$S = |-42.12| = 42.12$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (weld)

$P_L + P_b + Q = 42.12 < 52.5$ KSI (auto weld)

O.K.

Outside Surface

$\sigma_1 = -27.0$ KSI

$\sigma_2 = -20.0$ KSI

$\sigma_3 = 0$

$S_{12} = \sigma_1 - \sigma_2 = -27.0 - (-20.0) = -7.0$ KSI

$S_{23} = \sigma_2 - \sigma_3 = -20.0 - 0 = -20.0$ KSI

$S_{31} = \sigma_3 - \sigma_1 = 0 - (-27.0) = 27.0$ KSI

$S_m = |27.0| = 27.0$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (weld)

$P_L + P_b + Q = 27.0 < 52.5$ KSI (auto weld)

O.K.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria

BY_______ DATE_______ SUBJECT_______ SHEET NO. 24 OF_______

CHKD. BY_______ DATE_______ JOB NO._______

S3 to R3

Hydro Test Conditions

The hydro test pressure was assumed to be the max pressure at the bottom of the tunnel for the region under consideration.

Fig 14 Average net-section hoop stress P= 193 psi

Fig 15 Inside surface stress longitudinal & hoop P= 193 psi

Fig 16 Outside surface stress longitudinal + hoop P= 193 psi

Knuckle region at the small dia cyl.

$P_H = 1.5(119) + \text{water head}$

$P_H = 1.5(119) + 62.4 \frac{lb}{ft^3} \times \frac{1\ ft^2}{144\ in^2} \left[\frac{41}{2} + \frac{28.125}{2} \right] ft$

$P_H = 193$ psi

The max general membrane stress $\perp$ to a weld is smaller of

$P_m \leq 0.8\ (52.5) = 42.0$ KSI

or $P_m \leq 0.5(95) = 47.5$ KSI

The max. membrane stress in region (see Fig 14)

$52.0 > 42.0$ KSI

check to see if this stress is local stress

The stress exceed 1.1 (42) = 46.2 KSI for a meridional length of 16.5 in.

$$16.5'' < \sqrt{RT} = \sqrt{(14.06')(12)(1.75)} = 17.18''$$

∴ This area is a region of local membrane stress.

General Membrane Stress
(outside region of local membrane stress)

$$33.5 < 42.0 \text{ KSI}$$

∴ This knuckle region meets the stress evaluation criteria for hydro test conditions.

Knuckle region at the large dia. cylinder

$$P_H = 1.5\,(119) + 62.4 \times \frac{1}{144}\left[41.0\right]$$

$$P_H = 196 \text{ psi}$$

For the region of the knuckle at the large dia., the stress at hydro conditions

$$S_{HX} = \frac{196}{193}\left(S_{H_{193}}\right)$$

max membrane stress
see Fig 13

$$S_{HX} = \frac{196}{193}\left(-28.4\right) = -28.84 \text{ KSI } \left(\substack{\text{neg.}\\ \text{stress}}\right)$$

$$S_{HX} = \frac{196}{193}\left(38.0\right) = 38.59 \text{ KSI}$$

BY ______ DATE ______ SUBJECT ______ SHEET NO. 28 OF ______
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S3 to R3

38.59 < 42.0 KSI (for auto-weld)

∴ This Knuckle region meets the stress evaluation criteria for hydro test conditions.

BY ______ DATE ______	SUBJECT ______	SHEET NO. 29 OF ______
CHKD. BY ______ DATE ______	R6 to R9	JOB NO. ______

R6 to R9

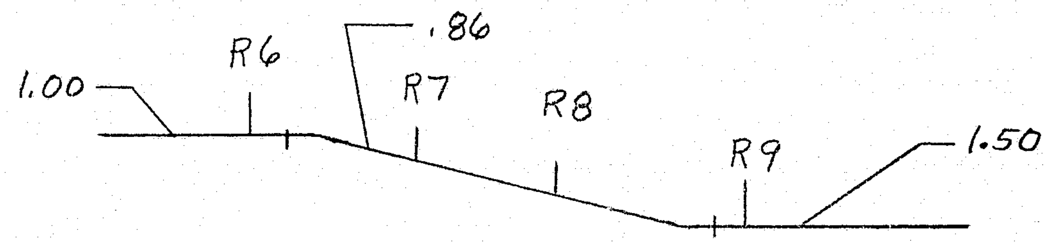


Fig 17 Computer plot of geometry

Fig 18 Average net-section hoop stress P = 119 psi

Fig 19 Inside surface stress longitudinal + hoop
P = 119 psi

Fig 20 Outside surface stress longitudinal + hoop
P = 119 psi

Fig 21 Radial displacement
P = 119 psi

Knuckle region at the small dia cylinder

Membrane stress (intensity)

Primary General membrane stress intensity

$$\sigma_1 = \frac{23.4 + 20}{2} = 21.7 \text{ KSI}$$

$$\sigma_2 = \frac{-4 + 18}{2} = 7.0 \text{ KSI}$$

$$\sigma_3 = -\frac{.119}{2} = -.06 \text{ KSI}$$

$$S_{12} = \sigma_1 - \sigma_2 = 21.7 - 7.0 = 14.7 \text{ KSI}$$

$$S_{23} = \sigma_2 - \sigma_3 = 7.0 - 0.06 = 6.93 \text{ KSI}$$

$$S_{31} = \sigma_3 - \sigma_1 = -0.06 - 21.7 = -21.76 \text{ KSI}$$

$$S = |-21.76| = 21.76 \text{ KSI}$$

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 20$ KSI

$\sigma_2 = -3$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 20 - (-3) = 23$ KSI

$S_{23} = -3 - (-.12) = -2.88$ KSI

$S_{31} = -.12 - 20.0 = -20.12$ KSI

$S = |-20.12| = 20.12$ KSI

Increase stress intensity for corner influence. (see p. 31C)

$S = 1.175(20.12) = 23.64$ KSI

$P_L + P_b + Q < \sigma_{yp}$

$26.64 < 52.5$ KSI (auto weld)

O.K.

This model did not consider the influence from CORNER # 1

The approximate influence from corner # 1 can be determined by noting the influence of corner # 4 on the cone / cylinder knuckle region.

From corner # 4 analysis, the max. Membrane stress intensity was 34.59 KSI.

From the SALORS analysis, the max. membrane stress intensity was 29.06 KSI

% increase due to corner influence

$$\frac{34.59 - 29.06}{34.59 \text{ KSI}} = 16 \text{ \% increase}$$

From corner # 4 analyses, the primary plus secondary stress intensity was

$S = 41.68$ KSI outside surface

$S = 41.21$ KSI inside surface

From SALOR Analyses;

Outside surface

$\sigma_1 = 33.0$ KSI

$\sigma_2 = 18.5$ KSI

$\sigma_3 = 0$

$S_{12} = 33.0 - 18.5 = 14.5$ KSI

$S_{23} = 18.5 - 0 = 18.5$ KSI

$S_{31} = 0 - 3 = -32.5$ KSI

$S = |-33| = 33.0$ KSI

Inside Surface

$\sigma_1 = 23.5$ KSI

$\sigma_2 = -10.5$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 23.5 - (-10.5) = 34.0$ KSI

$S_{23} = -10.5 - (-.12) = 10.38$ KSI

$S_{31} = -.12 - 23.5 = 23.62$ KSI

$S = |34.0| = 34.0$ KSI

% increase due to corner influence primary plus secondary stress intensity

Outside Surface

$$\frac{41.68 - 33.0}{41.68} = 20.8\%$$

Inside Surface

$$\frac{41.21 - 34.0}{41.21} = 17.5\%$$

Increase stress intensity at Knuckle near R9 by 16 %

$$S = 1.16\ (21.76) = 25.24\ KSI$$

$$P_m = 25.24 < S_m = 31.7\ KSI \qquad o.k.$$

General Principal membrane stress

$$\sigma = 18.0\ KSI$$

Increase by 16% due to corner influence

$$\sigma = 1.16\,(18.0) = 20.9\ KSI$$

$$20.9 < 23.7\ KSI$$

∴ The membrane stress (intensity) for this region meets the stress evaluation criteria

Outside Surface

$\sigma_1 = 26.0$ KSI

$\sigma_2 = 19.0$ KSI

$\sigma_3 = 0$

$S_{12} = 26.0 - 19.0 = 7.0$ KSI

$S_{23} = 19.0 - 0 = 19.0$ KSI

$S_{31} = 0 - 26.0 = -26.0$ KSI

$S = |-26.0| = 26.0$ KSI

Increase due to corner influence (p. 31C)

$S = 1.208(26) = 31.41$ KSI

$P_L + P_b + Q < \sigma_{YP}$

$31.41 < 52.5$ (auto weld)

O.K

∴ The primary plus secondary stress intensity meets the stress evaluation criteria.

Knuckle region at the large dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity
see Fig 18, 19 & 20

$\sigma_1 = 9.5$ KSI

$\sigma_2 = \frac{31.0 + (-7.5)}{2} = 11.75$ KSI

$\sigma_3 = -\frac{.119}{2} = -.06$ KSI

$S_{12} = 9.5 - 11.75 = -2.25$ KSI

$S_{23} = 11.75 - (-.06) = 11.82$ KSI

$S_{31} = -.06 - 9.5 = -9.56$ KSI

$S = |11.82| = 11.82$ KSI

$P_m = 11.82 < S_m = 31.7$ KSI O.K.

Since the stress intensity is $< S_m$ (31.7 KSI) the stress intensity meets the criteria for general membrane stress intensity

BY ______ DATE ______ SUBJECT ______ SHEET NO. 34 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______
R6 to R9

General Membrane stress

$S = 23.7$ KSI

$23.7 \leq 23.7$ KSI

The region meets the stress evaluation criteria for the general membrane stress.

Primary Plus Secondary Stress intensity

Inside Surface

$\sigma_1 = 15$ KSI

$\sigma_2 = 31$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 15 - 31 = 16$ KSI

$S_{23} = 31 - (-.12) = 31.12$ KSI

$S_{31} = -.12 - 15 = -15.12$ KSI

$S = |31.12| = 31.12$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (welds)

$P_L + P_b + Q = 31.12 < 52.5$ KSI   O.K.

Outside Surface

$\sigma_1 = 4.0$ KSI

$\sigma_2 = -7.5$ KSI

$\sigma_3 = 0$

$S_{12} = 4.0 - (-7.5) = 11.5$ KSI

$S_{23} = -7.5 - 0 = -7.5$ KSI

$S_{31} = 0 - 4.0 = -4.0$ KSI

$S = |11.5| = 11.5$ KSI

$P_L + P_b + Q < \sigma_{yp}$ (weld)

$P_L + P_b + Q = 11.15 < 52.5$ KSI (auto weld)

O.K.

The primary plus secondary stress intensity meets the stress evaluation criteria.

BY ____ DATE ____ SUBJECT ____ SHEET NO. 37 OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

R6 to R9

The stresses in the region of R 7 & R 8 are approximately the same as the knuckles regions. Since the stresses in the knuckles meet the criteria by a large margin, a detail summary of the stress at R7 & R8 is not given in the stress evaluation.

Hydro Test Condition

The hydro test pressure was assumed to be the max. pressure at the bottom of the tunnel for the region under consideration

Fig 22 Average net- section hoop stress P= 192 psi

Fig 23 Inside surface stress longitudinal + hoop P= 192

Fig 24 Outside surface stress longitudinal + hoop P= 192 psi

Knuckle region at the small dia cyl.

$P_H = 1.5(119) + \text{water head}$

$P_H = 1.5(119) + 62.4 \frac{lb}{ft^3} \times \frac{1}{144} \frac{ft^2}{in^2} \left(\frac{41'}{2} + \frac{18.75'}{2} \right)$

$P_H = 191.5 \text{ psi}$

The max general membrane stress $\perp$ to a weld is smaller of

$P_m \leq 0.8\,(52.5) = 42.0$ KSI

or

$P_m \leq 0.5(95) = 47.5$ KSI

The max. general membrane stress is 34.5 KSI (Fig 22)

The corner influence will be approximately 16% (see p. 31)

∴ General membrane stress is

$$S = 1.16(35.0) = 40.47 \text{ KSI}$$

$$40.47 < 42.0 \text{ KSI}$$

∴ This knuckle region meets the stress evaluation criteria for hydro test condition.

Knuckle region at the large dia. cyl.

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41}{2} + \frac{28.12}{2}\right]$$

$$P_H = 193 \text{ psi}$$

For the region of the knuckle at the large dia., the stress at hydro. condition

$$S_{Hx} = \frac{193}{191.5}\left(S_{H_{191.5}}\right)$$

max membrane stress (see Fig

$$S_{Hy} = \frac{193}{191.5}(38.2) = 38.50 \text{ KSI}$$

$$38.50 < 42.0 \text{ KSI} \qquad \text{O.K.}$$

$\therefore$ The knuckle region meets the stress evaluation criteria for hydro test conditions.

R10 to R12

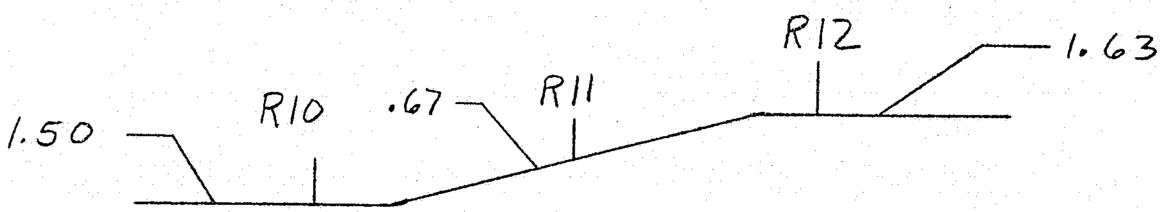


Fig 25 Computer plot of geometry

Fig 26 Average net-section hoop Stress P= 119 psi

Fig 27 Inside surface stress longitudinal + hoop P= 119 psi

Fig 28 Outside surface stress longitudinal + hoop P= 119 psi

Fig 29 Radial displacement P= 119 psi

The model did not consider the influence from corner # 1 and corner # 2.

% increase due to corner influence
See p. 31A, 31B, 31C

% increase 16 % membrane

% increase 20,8% outside surface

% increase 17.5% inside surface

BY ______ DATE ______ SUBJECT ______ SHEET NO. 44 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______
R10 to R12

Knuckle region at the small dia cylinder

Membrane stress (intensity)

Primary General Membrane Stress Intensity

$\sigma_1 = 23.7 \text{ KSI}$

$\sigma_2 = \left(\frac{-2.0 + 22.0}{2}\right) = 11.6 \text{ KSI}$

$\sigma_3 = -\frac{.119}{2} = -.06 \text{ KSI}$

$S_{12} = 23.7 - 11.6 = 12.1 \text{ KSI}$

$S_{23} = 11.6 - (-.06) = 11.66 \text{ KSI}$

$S_{31} = -.06 - 23.7 = -23.76$

$S = |-23.76| = 23.76 \text{ KSI}$

increase due to corner influence

$S = 1.16(23.76) = 27.56$

$P_m \leq S_m$

$27.56 < 31.7 \text{ KSI}$ O.K.

BY .... DATE .... SUBJECT .... SHEET NO. 45 OF ......

CHKD. BY .... DATE .... JOB NO. ....

R10 to R12

Max. Principal Membrane stress

$$S = 1.16\,(20.4) = 23.7 \text{ KSI} \qquad \text{O.K.}$$

The membrane stress (intensity) meets the stress evaluation criteria

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 23.0$ KSI

$\sigma_2 = -2.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 23.0 - (-2.0) = 25.0$ KSI

$S_{23} = -2.0 - (-.12) = -2.12$ KSI

$S_{31} = -.12 - 23 = 23.12$ KSI

$S = |25.0| = 25.0$ KSI

increased due to corner influence (p. 31C)

$S = 1.175 (25) = 29.37$ KSI

$P_L + P_b + Q < \sigma_{yp}$

$29.37 < 52.5$ KSI (auto weld)

O.K

Outside Surface

$\sigma_1 = 26.3$ KSI

$\sigma_2 = 22.3$ KSI

$\sigma_3 = 0$

$S_{12} = 26.3 - 22.3 = 4.0$ KSI

$S_{23} = 22.3 - 0 = 22.3$ KSI

$S_{31} = 0 - 26.3 = -26.3$ KSI

$S = |-26.3| = 26.3$ KSI

increase due to corner influence

$S = 1.208(26.3) = 31.77$ KSI

$P_L + P_b + Q < \sigma_{yp}$

$31.77 < 32.5$ KSI (auto weld) o.k.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria

Knuckle region at the large dia. Cylinder

Membrane stress (intensity)

Primary general membrane stress intensity

$$\sigma_1 = 24.0 \quad KSI$$

$$\sigma_2 = \left(\frac{8.0 + 17.0}{2}\right) = 12.5 \ KSI$$

$$\sigma_3 = -\frac{.119}{2} = -.06 \ KSI$$

$$S_{12} = 24.0 - 12.5 = 11.5 \quad KSI$$

$$S_{23} = 12.5 - (-.06) = 12.56 \quad KSI$$

$$S_{31} = -.06 - 24.0 = -24.06 \quad KSI$$

$$S = |-24.06| = 24.06 \quad KSI$$

increase due to corner

$$S = 1.16\,(24.06) = 27.91 \quad KSI$$

$$P_m \leq S_m$$

$$27.91 < 31.7 \ KSI \qquad O.K.$$

General membrane stress

$S = 23.0$ KSI outside local stress area at Knuckle

$23.0 < 23.7$ KSI O.K.

∴ The membrane stress (intensity) meets the stress evaluation criteria.

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 24.0$ KSI

$\sigma_2 = 12.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 24.0 - 12.0 = 12.0$ KSI

$S_{23} = 12.0 - (-.12) = 12.12$ KSI

$S_{31} = -.12 - 24.0 = -24.12$ KSI

$S = |-24.12| = 24.12$ KSI

Increase due to corner influence (p 31C)

$S = 1.175(24.12) = 28.34$ KSI

$P_L + P_b + Q < \sigma_{yp}$

$28.34 < 52.5$ KSI O.K.

Outside Surface

$\sigma_1 = 24.0$

$\sigma_2 = 16.0$

$\sigma_3 = 0$

$S_{12} = 24.0 - 16.0 = 8.0$ KSI

$S_{23} = 16.0 - 0 = 16.0$ KSI

$S_{31} = 0 - 24.0 = -24.0$ KSI

$S = |-24.0| = 24.0$ KSI

increase due to corner influence

$S = 1.208\,(24) = 28.99$ KSI

$P_L + P_b + Q < \sigma_{yp}$

$28.99 < 52.5$ KSI (auto weld)

O.K.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria

Hydro test conditions

The hydro test pressure was assumed to be the max. pressure at the bottom of the tunnel for the region under consideration.

Fig 30 Average net-section hoop stress P= 192 psi

Fig 31 Inside surface stress longitudinal + hoop P= 192 psi

Fig 32 Outside surface stress longitudinal + hoop P= 192 psi

BY ______ DATE ______	SUBJECT ______	SHEET NO. 53 OF ______
CHKD. BY ______ DATE ______	R10 to R12	JOB NO. ______

Knuckle region at the small dia. cyl.

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41'}{2} + \frac{18.75'}{2}\right]$$

$$P_H = 191.5$$

The max general membrane stress $\perp$ to a weld is smaller of

$P_m \leq 0.8(52.5) = 42.5$ KSI (auto weld)

or

$P_m \leq 0.5(95) = 47.5$ KSI

The max membrane stress in this region (see Fig 30)

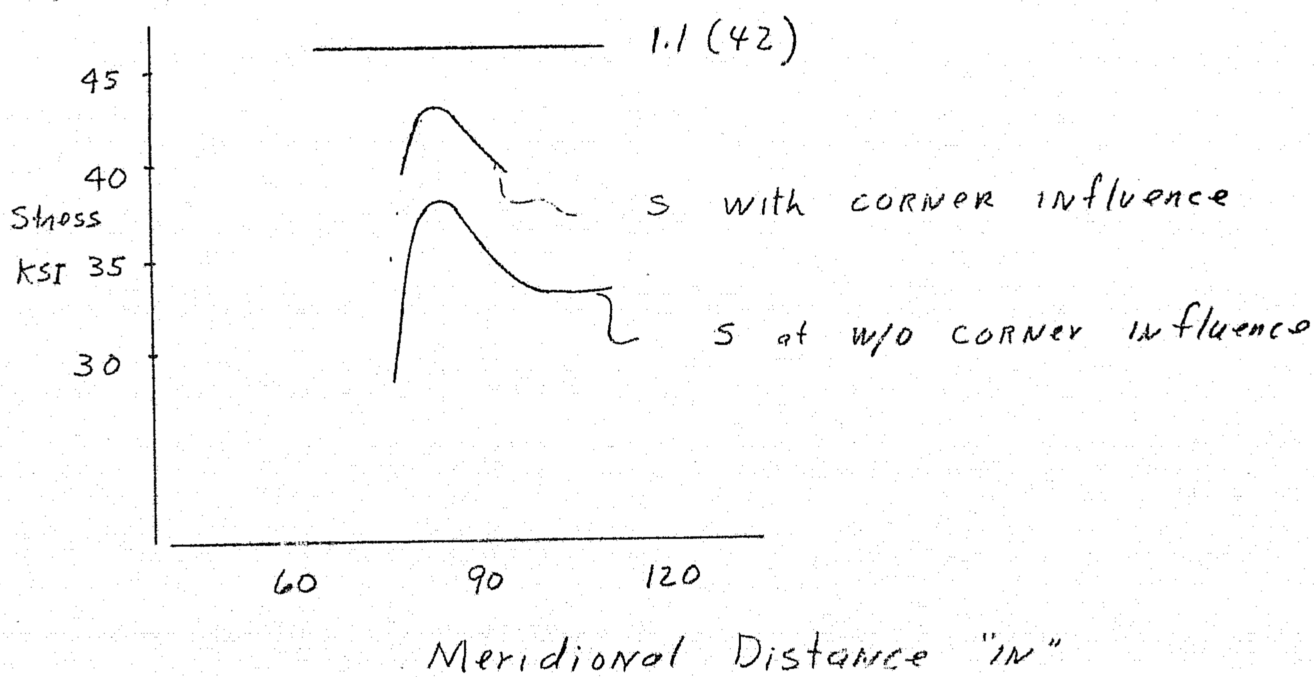
$S = 38.5$

Due to the influence of corner #1 (see p. 31), increase the stress 16%

$S = 1.16(38.) = 44.1$ KSI

$44.1 > 42.5$ KSI for auto weld.

check to see if this stress is local stress.



At a stress of $1.1(42) = 46.2$ KSI the stress extends over a meridional distance of 0. since the max. stress is < 46.2 KSI

$0 < \sqrt{RT}$

∴ this stress is local

Max stress outside local stress region

$$S = 1.16 (32.5) = 37.7 \text{ KSI}$$

$37.7 < 42$ KSI (σ_{YP} for auto weld)

$\therefore$ The regions meets the stress criteria for hydro test conditions.

Knuckle region at the large dia Cyl.

$$P_H = 1.5\,(119) + 62.4 \times \frac{1}{144}\left(\frac{41}{2} + \frac{22}{2}\right)$$

$$P_H = 192 \text{ psi}$$

The max membrane stress in this region (see Fig 30)

$$S = 37.8 \text{ KSI}$$

Due to the influence of corner #2 (see p. 31), increase the stress by 16%

$$S = 1.16\,(37.8) = 43.85 \text{ KSI}$$

$$43.85 > 42.5 \quad (\sigma_{yp} \text{ for auto weld})$$

check to see if this stress is local

The stress (43.85 KSI) $<$ 1.1(42) = 46.2 KSI

$\therefore$ The meridional length over which the stress (1.1 x 42) exist is 0

$$0 < \sqrt{RT}$$

$\therefore$ This stress is a local stress

Max stress outside region of local stress

$$S = 1.16(36) = 41.76 \text{ KSI}$$

$$41.76 < 42 \text{ KSI} \qquad \text{O.K.}$$

$\therefore$ This region meets the stress evaluation criteria for hydro test conditions.

R13A to S8

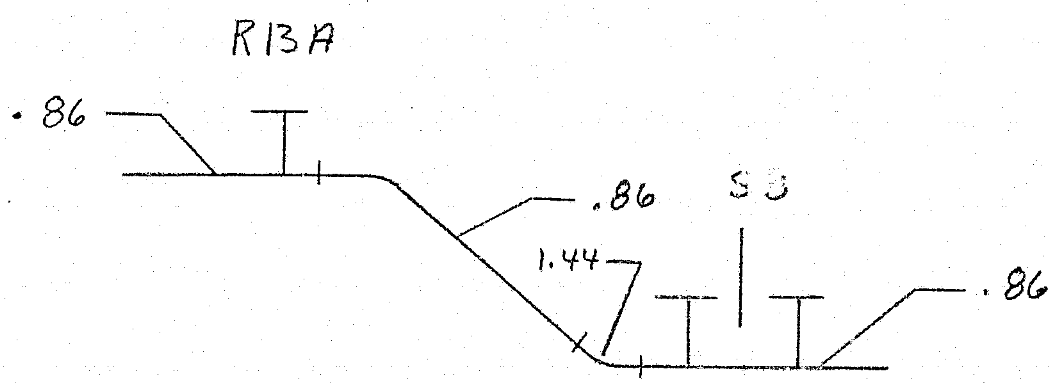


Fig 33 Computer plot of geometry

Fig 34 Average net-section hoop stress
p = 119 psi

Fig 35 Inside surface stress
Longitudinal & hoop
P = 119 psi

Fig 36 Outside surface stress
longitudinal & hoop
P = 119 psi

Fig 37 Radial displacement
P = 119 psi

Knuckle region at the small dia Cylinder

Membrane Stress (Intensity)

see Fig

$\sigma_1 = 30.8$ KSI

$\sigma_2 = \frac{-9.5 + 21.0}{2} = 5.75$ KSI

$\sigma_3 = -\frac{.119}{2} = -.06$ KSI

$S_{12} = 30.8 - 5.75 = 25.05$ KSI

$S_{23} = 5.75 - (-.06) = 5.81$ KSI

$S_{31} = -.06 - 30.8 = -30.86$ KSI

$S = |-30.86| = 30.86$ KSI

$P_m = 30.86 < 31.7$ KSI

∴ This region meets the criteria for a primary general membrane stress intensity

General principal membrane stress

$S = 19.0$ KSI

$19 < 23.7$ O.K.

The membrane stress (intensity) for this region meets the stress evaluation criteria.

BY ________ DATE ________ SUBJECT ________ SHEET NO. 61 OF ____

CHKD. BY ______ DATE ________ JOB NO. ________

R13A to S8

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 27.0$ KSI

$\sigma_2 = -9.5$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 27.0 - (-9.5) = 36.5$ KSI

$S_{23} = -9.5 - (-.119) = 9.381$ KSI

$S_{31} = -.119 - 27. = 27.119$ KSI

$S = |36.5| = 36.5$ KSI

$P_L + P_b + Q = 36.5 < 52.5$ (σ_{YP} for auto welds)

O.K.

Outside Surface

$\sigma_1 = 35.5$ KSI

$\sigma_2 = 21.0$ KSI

$\sigma_3 = 0$

$S_{12} = 35.5 - 21.0 = 14.5$ KSI

$S_{23} = 21.0 - 0 = 21.0$ KSI

$S_{31} = 0 - 35.5 = -35.5$ KSI

$S = |-35.5| = 35.5$ KSI

$P_L + P_b + Q = 35.5 < 52.5$ (σ_{yp} for auto welds)

O.K.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria

Knuckle region at the large dia. cyl.

Membrane stress (intensity)

see Fig. 34

$$\sigma_1 = -13.8 \text{ KSI}$$

$$\sigma_2 = \frac{42 + (-21)}{2} = 10.5 \text{ KSI}$$

$$\sigma_3 = -\frac{.119}{2} = -.06 \text{ KSI}$$

$$S_{12} = -13.8 - 10.5 = -24.3 \text{ KSI}$$

$$S_{23} = 10.5 - (-.06) = 10.56 \text{ KSI}$$

$$S_{31} = -.06 - (-13.8) = 13.74 \text{ KSI}$$

$$S = |-24.3| = 24.3 \text{ KSI}$$

$$P_m = 24.3 < 31.7 \text{ KSI} \quad \text{O.K.}$$

General Principal membrane stress

$S = 22.3$

$22.3 < 23.7$ O.K.

The membrane stress (intensity) in this region meets the stress evaluation criteria.

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = -4.0$ KSI

$\sigma_2 = 42.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = -4.0 - 42.0 = -46.0$ KSI

$S_{23} = 42.0 - (-.119) = 42.119$ KSI

$S_{31} = -.119 - (-4.0) = -3.881$ KSI

$S = |-46.0| = 46.0$ KSI

$P_L + P_b + Q = 46.0 < 52.5$ KSI (σ_{yp} of auto welds)

O.K.

Outside Surface

$\sigma_1 = -23$ KSI

$\sigma_2 = -21$ KSI

$\sigma_3 = 0.0$

$S_{12} = -23. - (-21) = -2$ KSI

$S_{23} = -21.0 - 0 = -21$ KSI

$S_{31} = 0 - (-23) = 23$ KSI

$S = |+23.0| = 23$ KSI

$P_L + P_b + Q = 23 < 52.5$ (σ_{yp} of auto welds)

O.K.

The primary plus secondary stress intensity meets the stress evaluation criteria.

Hydro Test Condition

The hydro test pressure was assumed to be the max. pressure at the bottom of the tunnel for the region under consideration.

Fig 38 Average net-section hoop stress $P = 196$ psi

Fig 39 Inside surface stress longitudinal + hoop $P = 196$ psi

Fig 40 Outside surface stress longitudinal + hoop $P = 196$ psi

Knuckle region at the small dia cyl.

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41}{2} + \frac{22}{2} + 7.60\right]$$

$$= 195.5 \text{ psi}$$

The max general membrane stress $\perp$ to a weld is smaller of

$P_m \leq 0.8\ (52.5) = 42$ (auto weld)

or

$P_m \leq 0.5\ (95.0) = 47.5$

The max. stress in this region is (see Fig 38)

$S = 50.35$ KSI

$50.35 > 42$ KSI

Check to see if this stress is local stress

The stress exceeds $1.1(42) = 46.2$ KSI for a meridinal length of 12.5 in.

$$12.5'' < \sqrt{RT} = \sqrt{11'(12)(1.44)} = 13.79''$$

∴ This area is a region of local membrane stress.

General membrane stress
(outside region of local membrane stress)

$$S = 31.0 \text{ KSI}$$

$$31.0 < 42.0 \text{ KSI}$$

∴ This region meets the stress evaluation criteria for hydro test conditions.

Knuckle region at the large dia.

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41}{2} + \frac{25}{2} + 7.60\right]$$

$$P_H = 196 \text{ psi}$$

For this region, the stress at hydro conditions

$$S_{Hx} = \frac{196}{195.5}\left(S_{H_{195.5}}\right)$$

max. membrane stress
(see Fig.

$$S_{Hx} = \frac{196}{195.5}(36.7) = 36.8 \text{ KSI}$$

$$36.8 < 42.0 \text{ KSI} \qquad \text{(for auto welds)}$$

∴ This region meets the stress evaluation criteria for hydro test condition

S9 to R15 A

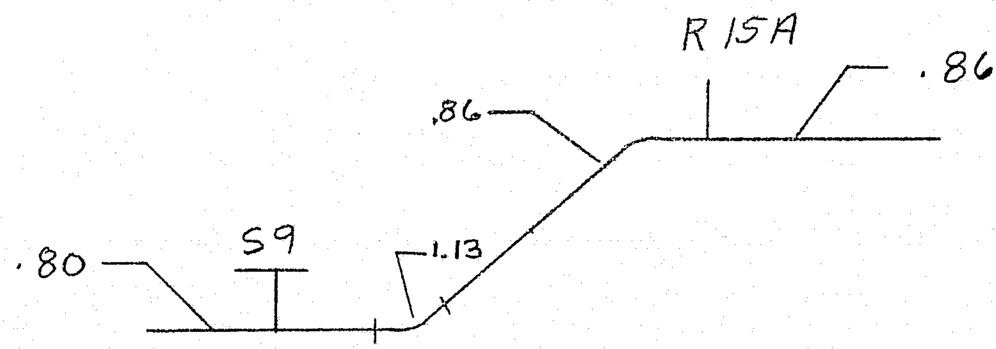


Fig 41 Computer plot of geometry

Fig 42 Average net-section hoop stress
P= 119 psi

Fig 43 Inside surface stress
Longitudinal + hoop
P= 119 psi

Fig 44 Outside surface stress
Longitudinal + hoop
P= 119 psi

Fig 45 Radial displacement
P= 119 psi

Knuckle region at the small dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity
see figs 42, 43 + 44

$\sigma_1 = 32.0$ KSI

$\sigma_2 = \frac{-10.0 + 22.5}{2} = 6.25$ KSI

$\sigma_3 = \frac{-.119}{2} = -.06$ KSI

$S_{12} = 32.0 - 6.25 = 25.75$ KSI

$S_{23} = 6.25 - (-.06) = 6.31$ KSI

$S_{31} = -.06 - 32.0 = -32.06$ KSI

$S = |-32.06| = 32.06$ KSI

$P_L = 32.06 < 1.5(31.7) = 47.5$ KSI

O.K.

This stress intensity (32.06 KSI) < 1.1(31.7) = 34.87 KSI.

∴ The meridional length over which the stress exist is 0

∴ This stress is a local membrane stress intensity.

General Membrane Stress Intensity

$\sigma_1 = 18.0$ KSI

$\sigma_2 = \frac{14 + 4.2 \text{ KSI}}{2} = 9.1$ KSI

$\sigma_3 = -\frac{.119}{2} = -.06$ KSI

$S_{12} = 18.0 - 9.1 = 8.9$ KSI

$S_{23} = 9.1 - (-.06) = 9.16$ KSI

$S_{31} = -.06 - 18.0 = -18.06$ KSI

$$S = |-18.06| = 18.06 \text{ KSI}$$

$$P_m = 18.06 \leq 31.7 \text{ KSI} \qquad \text{O.K.}$$

General principal membrane stress

$$S = 18.0 \text{ KSI}$$

$$18.0 < 23.7 \text{ KSI} \qquad \text{O.K.}$$

The membrane stress (intensity) meets the stress evaluation criteria.

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = 27.0$ KSI

$\sigma_2 = -10.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = 27 - (-10.0) = 37.0$ KSI

$S_{23} = -10.0 - (-.12) = 9.88$ KSI

$S_{31} = -.12 - 27.0 = 27.12$ KSI

$S = |37.0| = 37.0$ KSI

$P_L + P_b + Q < \sigma_{yp}$ (auto weld)

$37.0 < 52.5$ KSI O.K.

Outside Surface

$\sigma_1 = 37.0$ KSI

$\sigma_2 = 22.5$ KSI

$\sigma_3 = 0$

$S_{12} = 37.0 - 22.5 = 14.5$ KSI

$S_{23} = 22.5 - 0 = 22.5$ KSI

$S_{31} = 0 - 37.0 = -37.0$ KSI

$S = |-37.0| = 37.0$ KSI

$P_L + P_b + Q < \sigma_{YP}$ (auto weld)

$37.0 < 52.5$ KSI   O.K.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria.

Knuckle region at the large dia cylinder

Membrane Stress (intensity)

$\sigma_1 = -15.2$

$\sigma_2 = \dfrac{42 - 21.0}{2} = 10.5$

$\sigma_3 = -\dfrac{.119}{2} = -.06$ KSI

$S_{12} = -15.2 - 10.5 = 25.7$ KSI

$S_{23} = 10.5 - (-.06) = 10.56$ KSI

$S_{31} = -.06 - (-15.2) = 15.14$ KSI

$S_m = |25.7| = 26.2$ KSI

$S < 31.7$ KSI

$P_m = 25.7 < 31.7$ KSI

∴ Meets criteria for primary general membrane stress intensity

General Membrane stress

$S = 23.2$ KSI

$23.2 < 23.7$ KSI O.k.

∴ The membrane stress (intensity) meets the stress evaluation criteria

Primary Plus Secondary Stress Intensity

Inside Surface

$\sigma_1 = -6.0$ KSI

$\sigma_2 = 41.0$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = -6.0 - 41.0 = -47.0$ KSI

$S_{23} = 41.0 - (-.119) = 41.119$ KSI

$S_{31} = -.119 - (-6.0) = 5.881$ KSI

$S = |-47.0| = 47.0$ KSI

$P_L + P_b + Q < \sigma_{yp}$ (auto welds)

$47.0 < 52.5$ KSI O.K.

Outside Surface

$\sigma_1 = -25.0$ KSI

$\sigma_2 = -21.0$ KSI

$\sigma_3 = 0$

$S_{12} = -25.0 - (-21.0) = -4.0$ KSI

$S_{23} = -21.0 - 0 = -21.0$ KSI

$S_{31} = 0 - (-25.0) = 25.0$ KSI

$S = |25.0| = 25.0$ KSI

$P_L + P_b + Q < \sigma_{yp}$ (auto welds)

$25.0 < 52.5$ KSI O.K.

∴ The primary plus secondary stress intensity meets the stress evaluation criteria.

Hydro Test Conditions

The hydro test pressure was assumed to be the max. pressure at the bottom of the tunnel for the region under consideration.

Fig 46 Average net-section hoop stress $P = 195$ psi

Fig 47 Inside surface stress longitudinal + hoop $P = 195$ psi

Fig 48 Outside surface stress longitudinal + hoop $P = 195$ psi

Knuckle region at the small dia cyl.

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41}{2} + \frac{18.33}{2} + 7.60\right]$$

$$P_H = 194.6$$

The max general membrane stress $\perp$ to a weld is smaller of

$$P_m \leq 0.8(52.5) = 42.0 \text{ KSI}$$

or

$$P_m \leq 0.5(95.0) = 47.5 \text{ KSI}$$

The max. stress in this region (see Fig) is

$$S = 50.96 \text{ KSI}$$

$$50.96 > 42.0 \text{ KSI}$$

check to see if this is local stress

The stress exceeds $1.1(42) = 46.2$ KSI for a meridional distance of 10.5

$$10.5'' < \sqrt{RT} = \sqrt{(9.167)'(12)(1.13)} = 11.15''$$

∴ This area is a region of local membrane stress.

General membrane stress
(outside area of local stress)

$$S = 31.0$$

$$31.0 < 42 \qquad \text{O.K.}$$

This knuckle region meets the stress criteria for hydro test condition

Knuckle region at the large dia Cylinder

$$P_H = 1.5(119) + 62.4 \times \frac{1}{144}\left[\frac{41}{2} + \frac{22}{2} + 7.60\right]$$

$$P_H = 195.5$$

For this region, the stress at hydro condition is

$$S_{Hx} = \frac{195.5}{194.6}\left(S_{H_{194.6}}\right)$$

Max membrane stress

$$S_{Hx} = \frac{195.5}{194.6}(-23.4) = -23.5 \text{ KSI}$$

$$S_{Hx} = \frac{195.5}{194.6}(37.2) = 37.4 \text{ KSI}$$

$37.4 < 42.0$ KSI O.K.

∴ This knuckle region meets the criteria for hydro test conditions.

S9 to R21.

This region of the tunnel is a long shallow cone. The cone angle for the cone is shallower than the cone angle for the the region between R6 + R9. Due to the fact shallow cone angles do not produce high stresses at the knuckles (Ref Fig 17 thru 20) and the evaluation of R6 to R9 cone p. 29 thru 41) the area was not analyzed by finite difference methods.

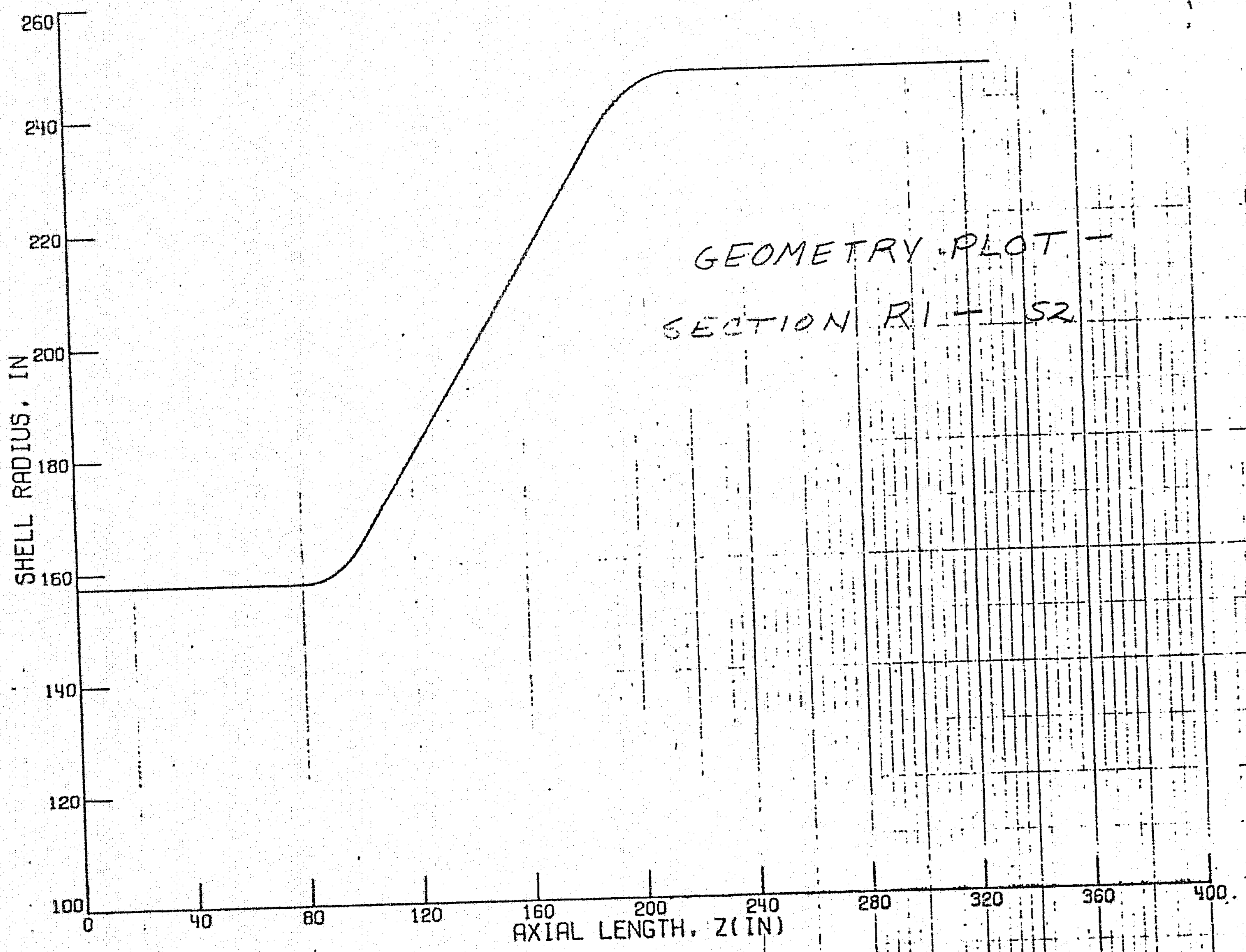

GEOMETRY PLOT —
SECTION R1 — S2
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure 1

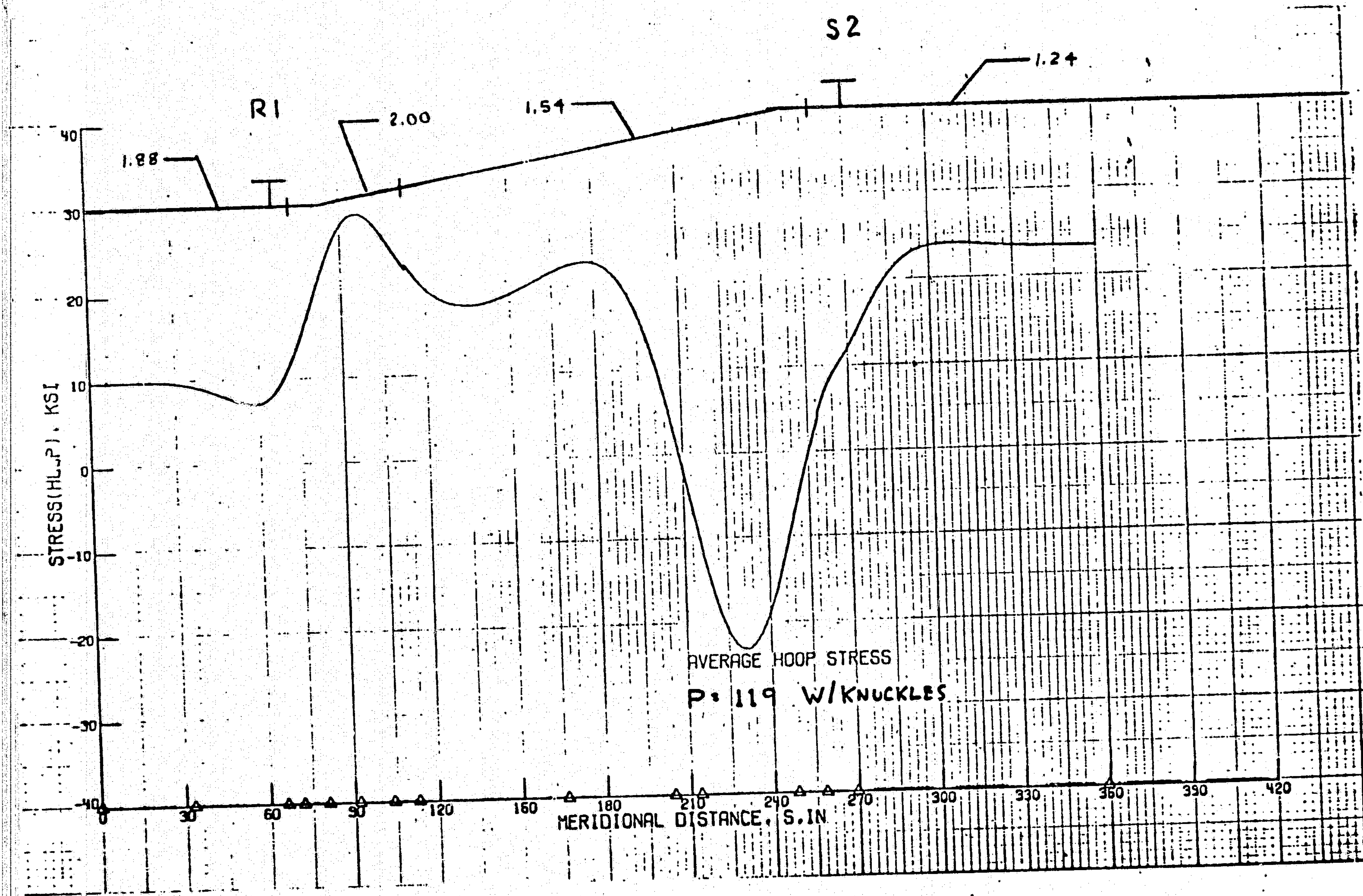
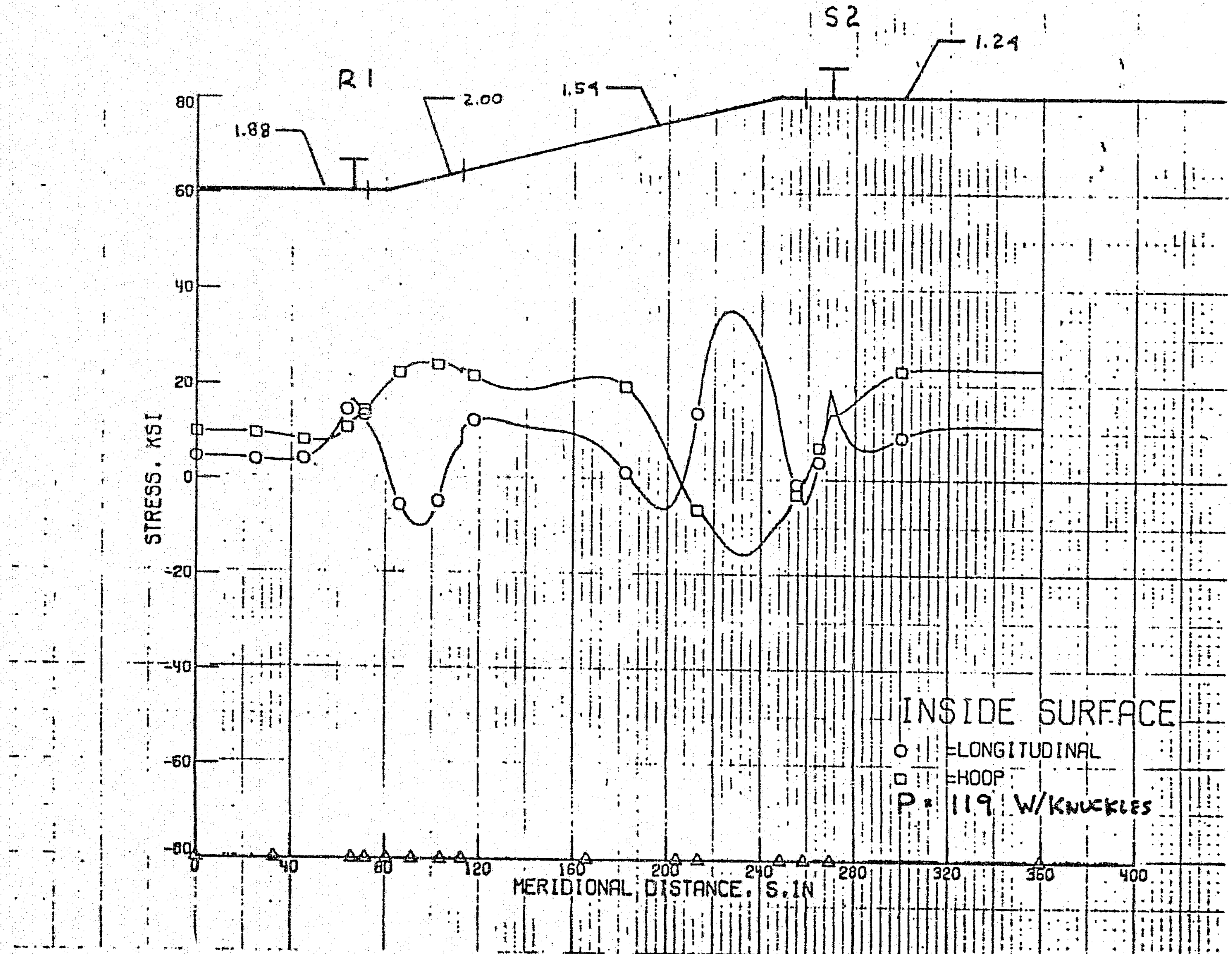

S2
R1
1.88
2.00
1.54
1.24
STRESS(HL,P), KSI
40
30
20
10
0
-10
-20
-30
-40
0
30
60
90
120
160
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
AVERAGE HOOP STRESS
P: 119 W/KNUCKLES

Figure 2



S2
R1
1.88
2.00
1.54
1.24
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 119 W/KNUCKLES

Figure 3

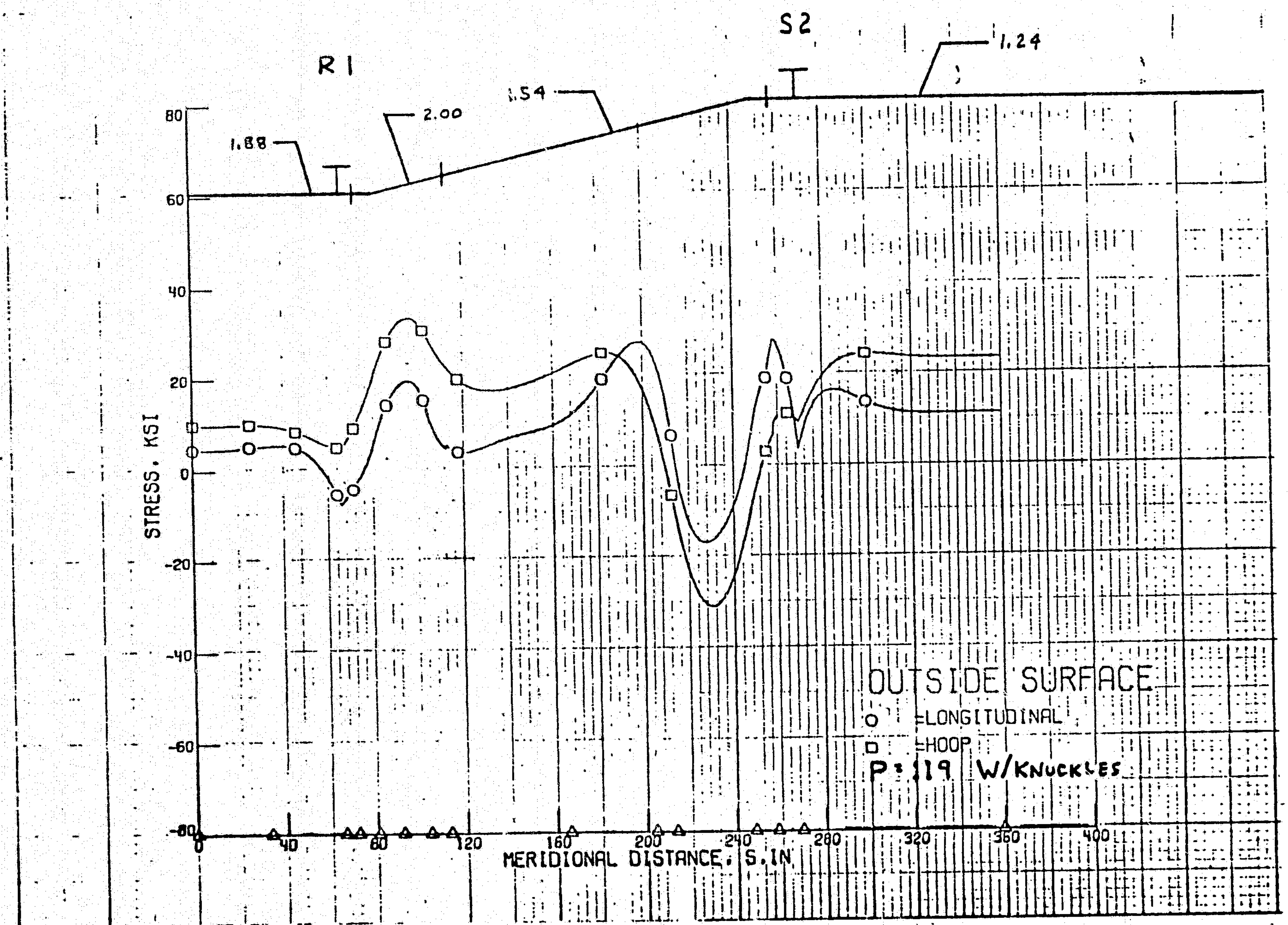
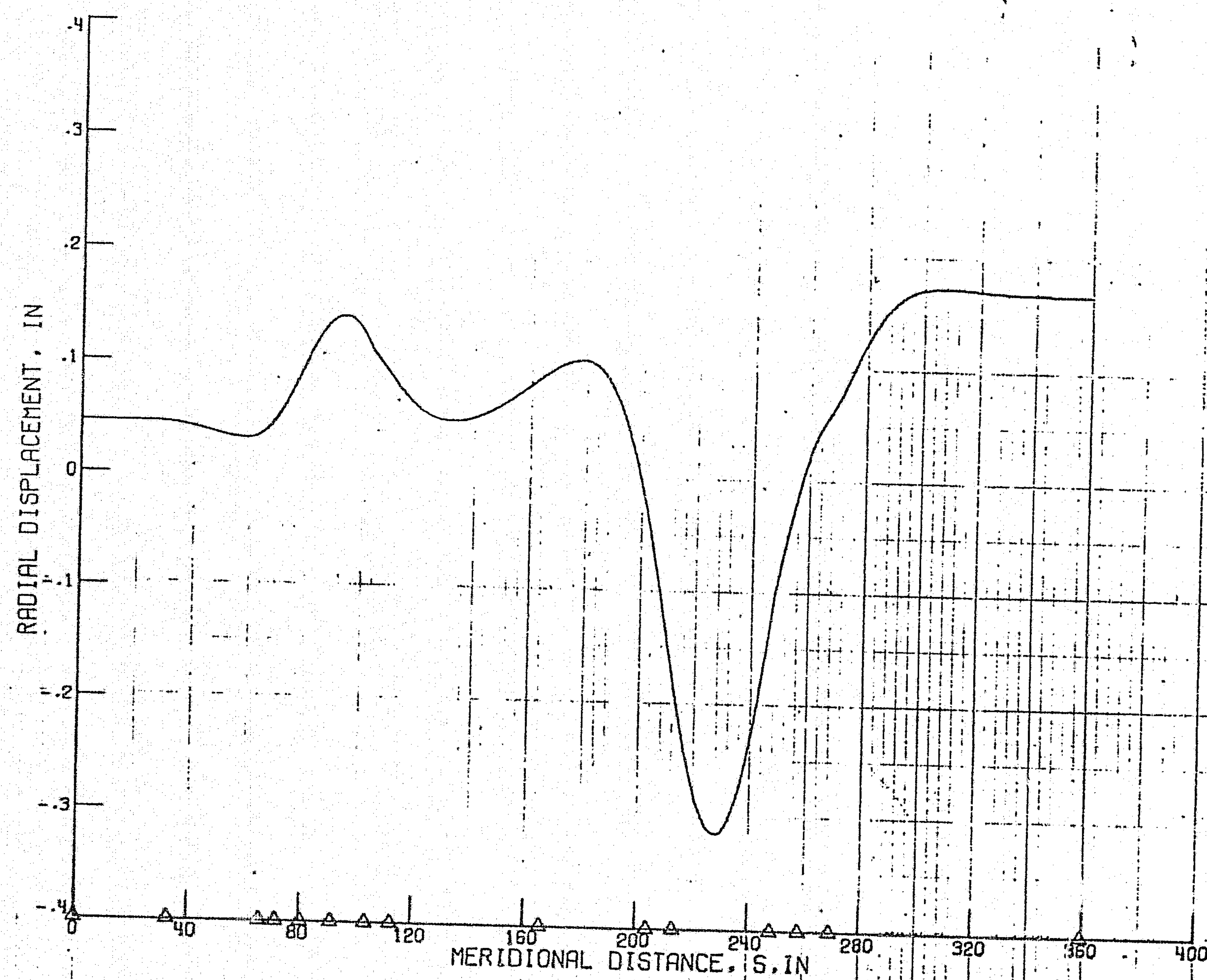


Figure 4

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR



RADIAL DISPLACEMENT, IN
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN

Figure 5

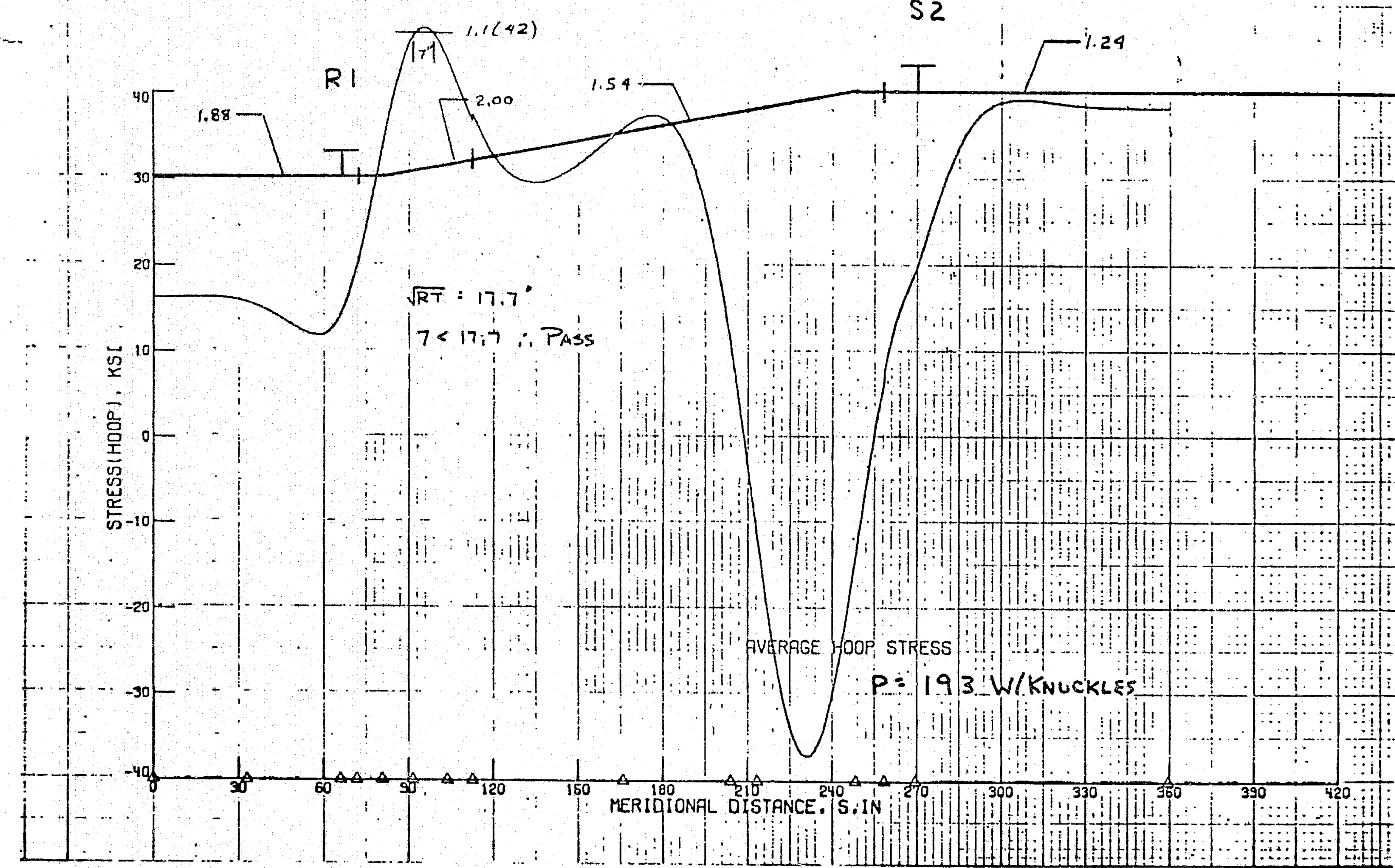

S2
R1
1.1(42)
|7|
1.24
2.00
1.54
1.88
$\sqrt{RT}$: 17.7
7 < 17.7 ∴ PASS
AVERAGE HOOP STRESS
P = 193 W/KNUCKLES
STRESS(HOOP), KSI
MERIDIONAL DISTANCE, S, IN
40
30
20
10
0
-10
-20
-30
-40
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420

Figure 6

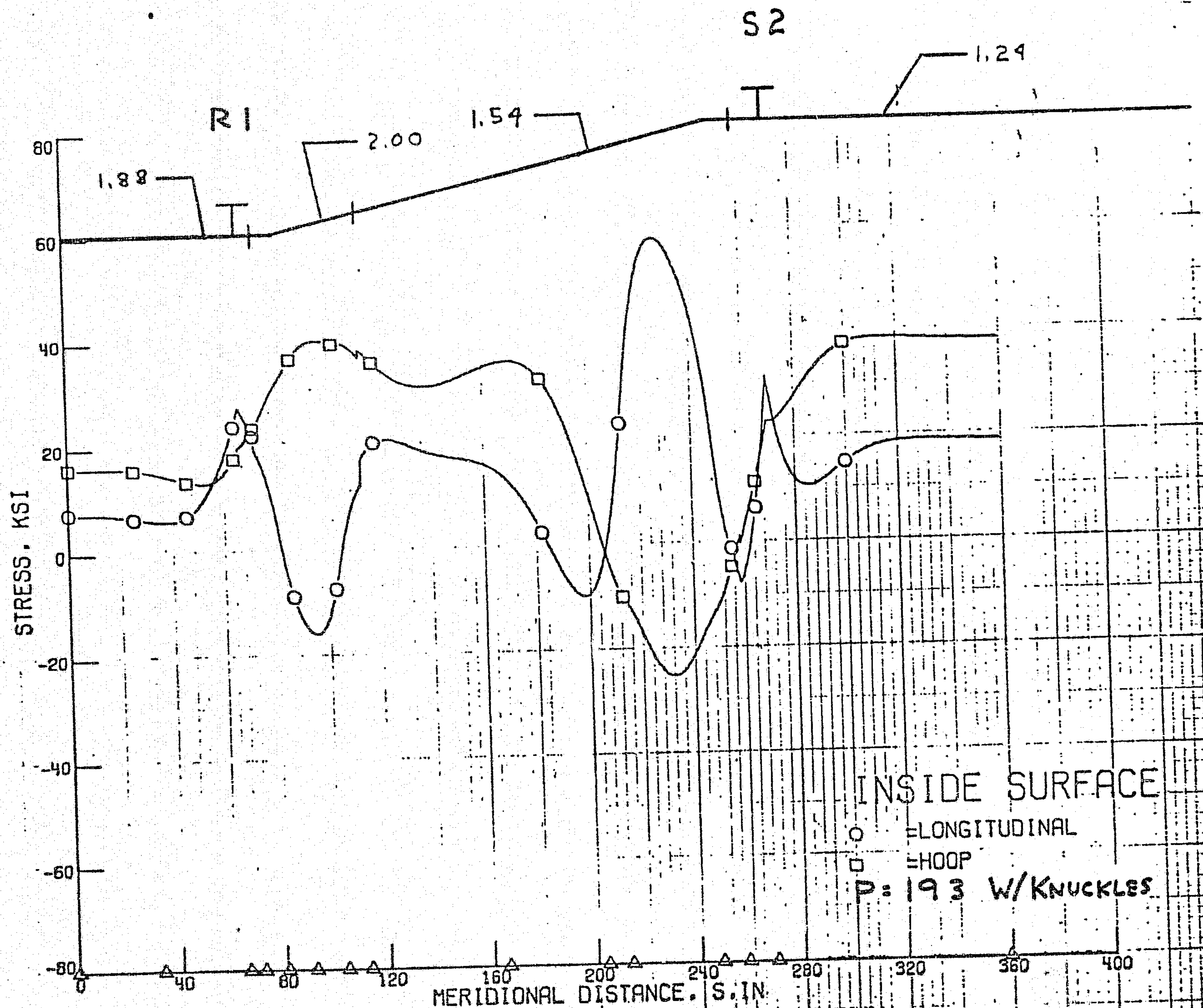

S2
R1
1.88
2.00
1.54
1.24
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P: 193 W/KNUCKLES

Figure 7

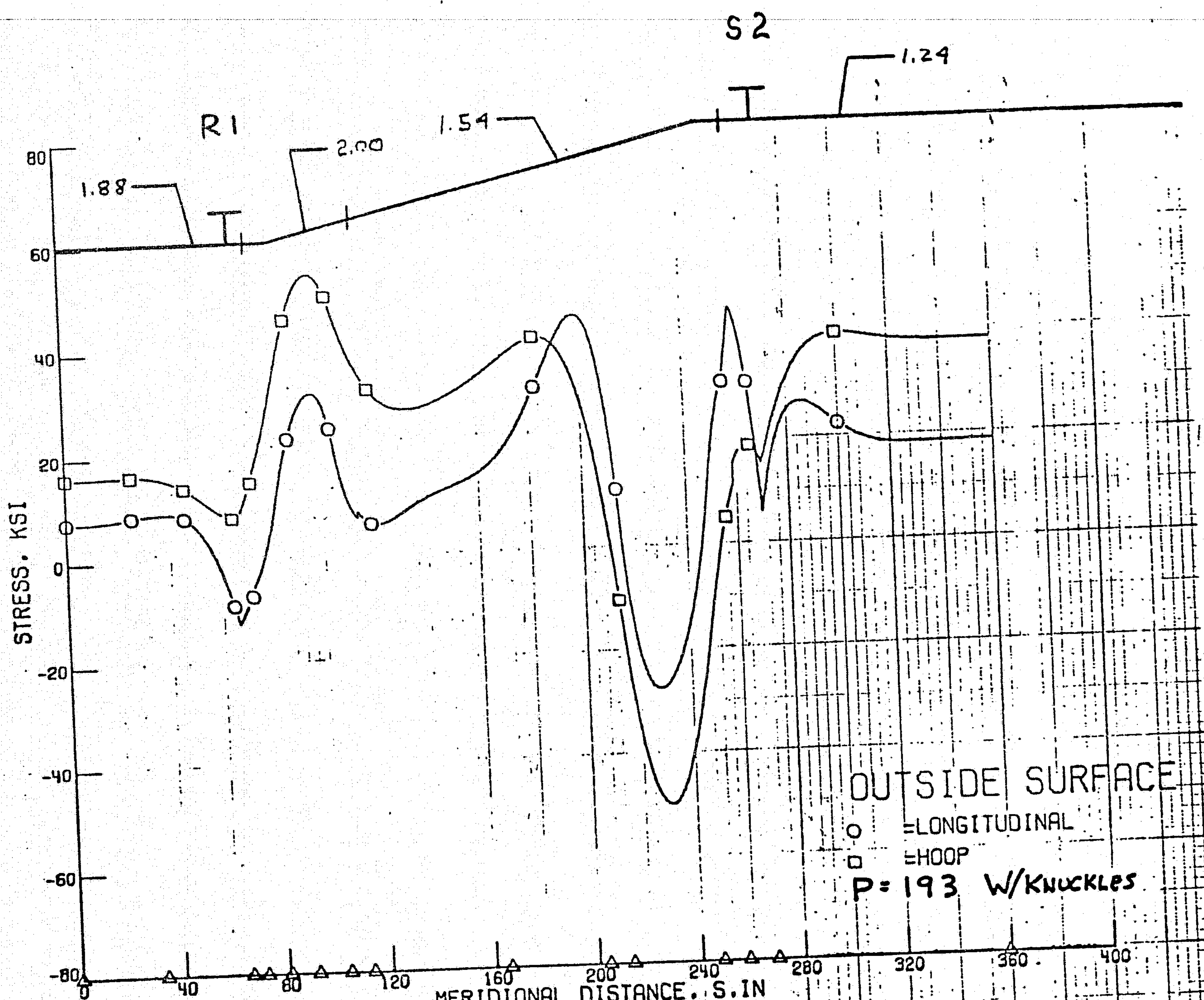
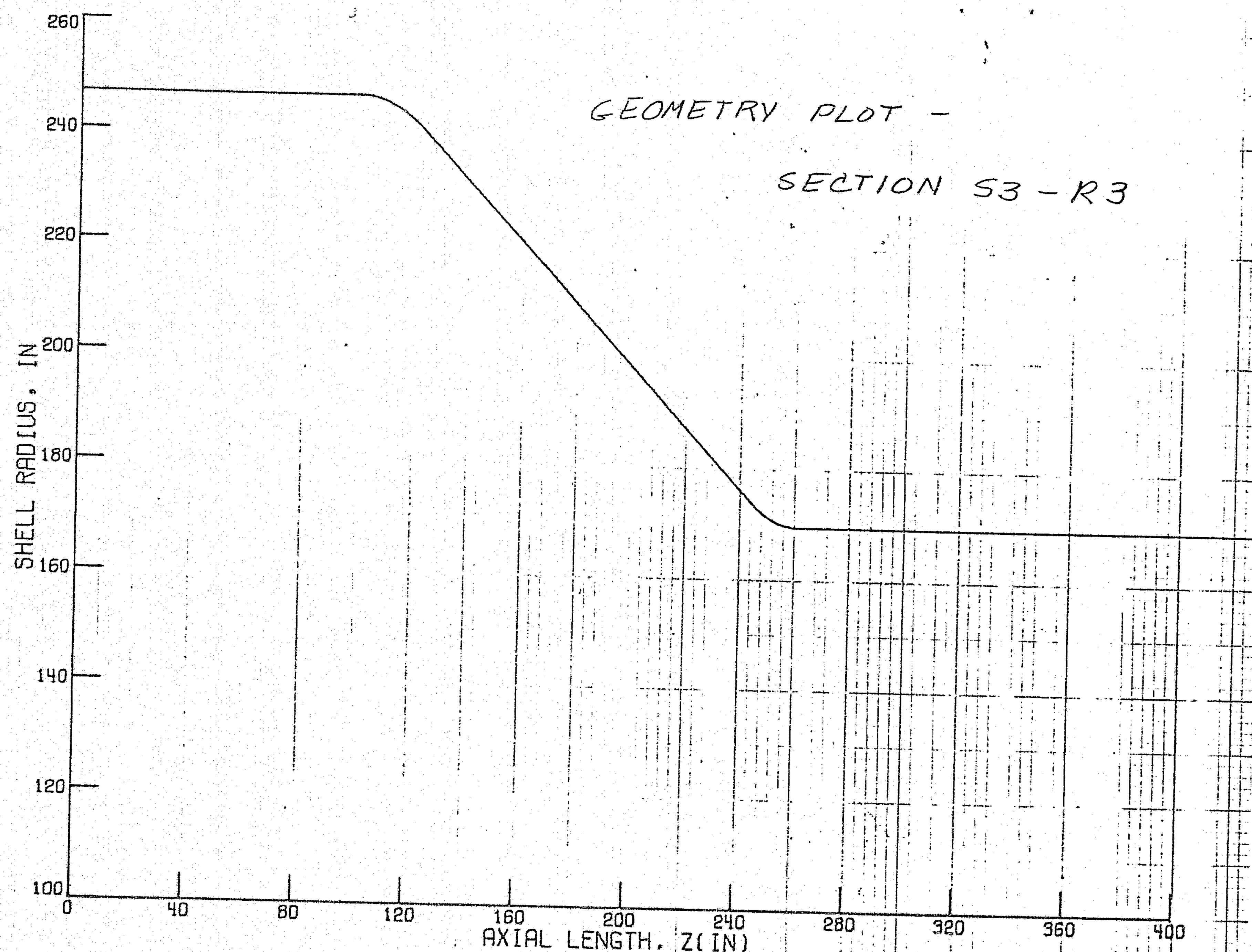

S2
R1
1.24
1.54
2.00
1.88
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P= 193 W/KNUCKLES

Figure 8



GEOMETRY PLOT -
SECTION S3 - R3
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure 9

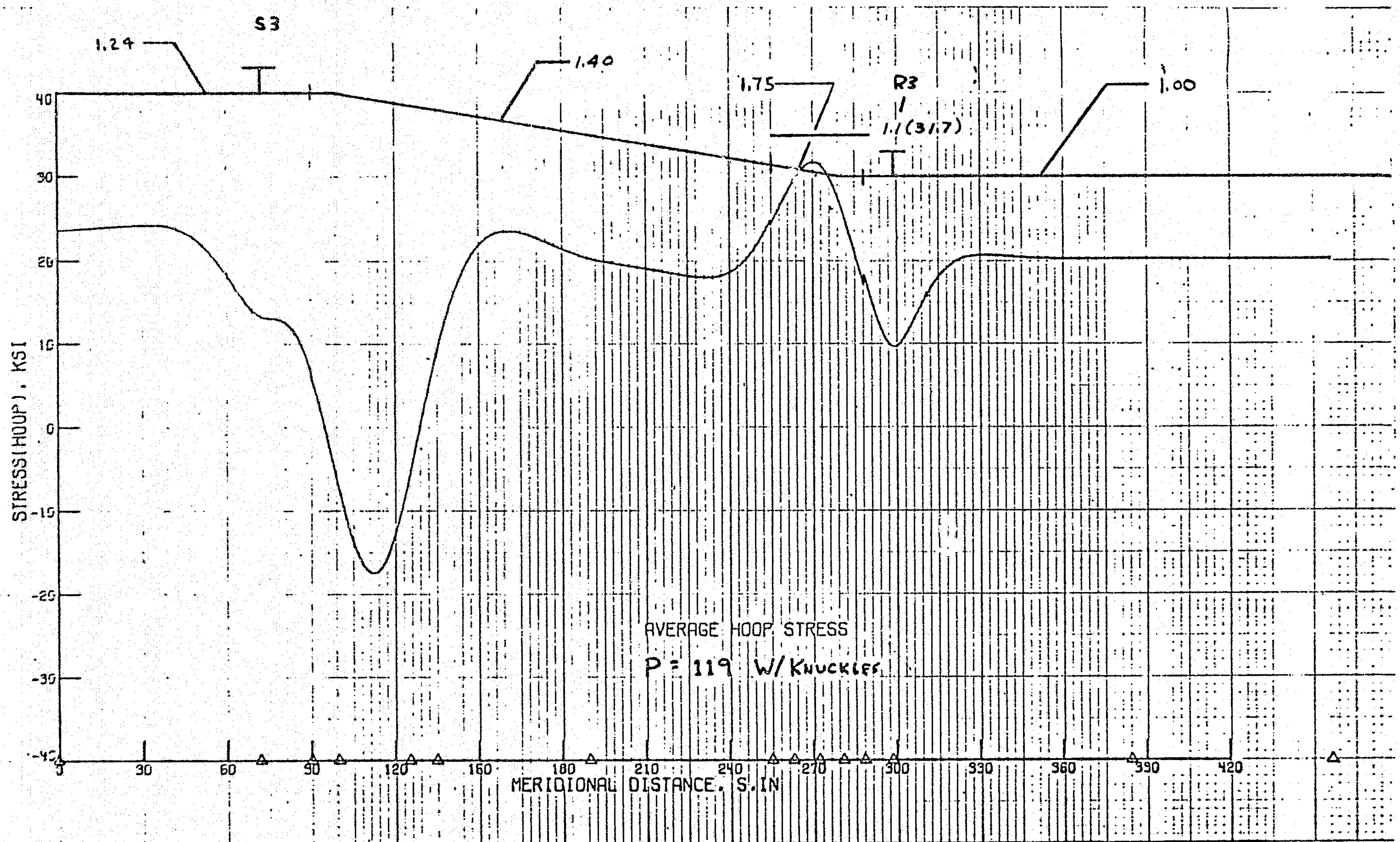

S3
1.24
1.40
1.75
R3
1.1 (31.7)
1.00
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S,IN
AVERAGE HOOP STRESS
P = 119 W/KNUCKLES

Figure 10

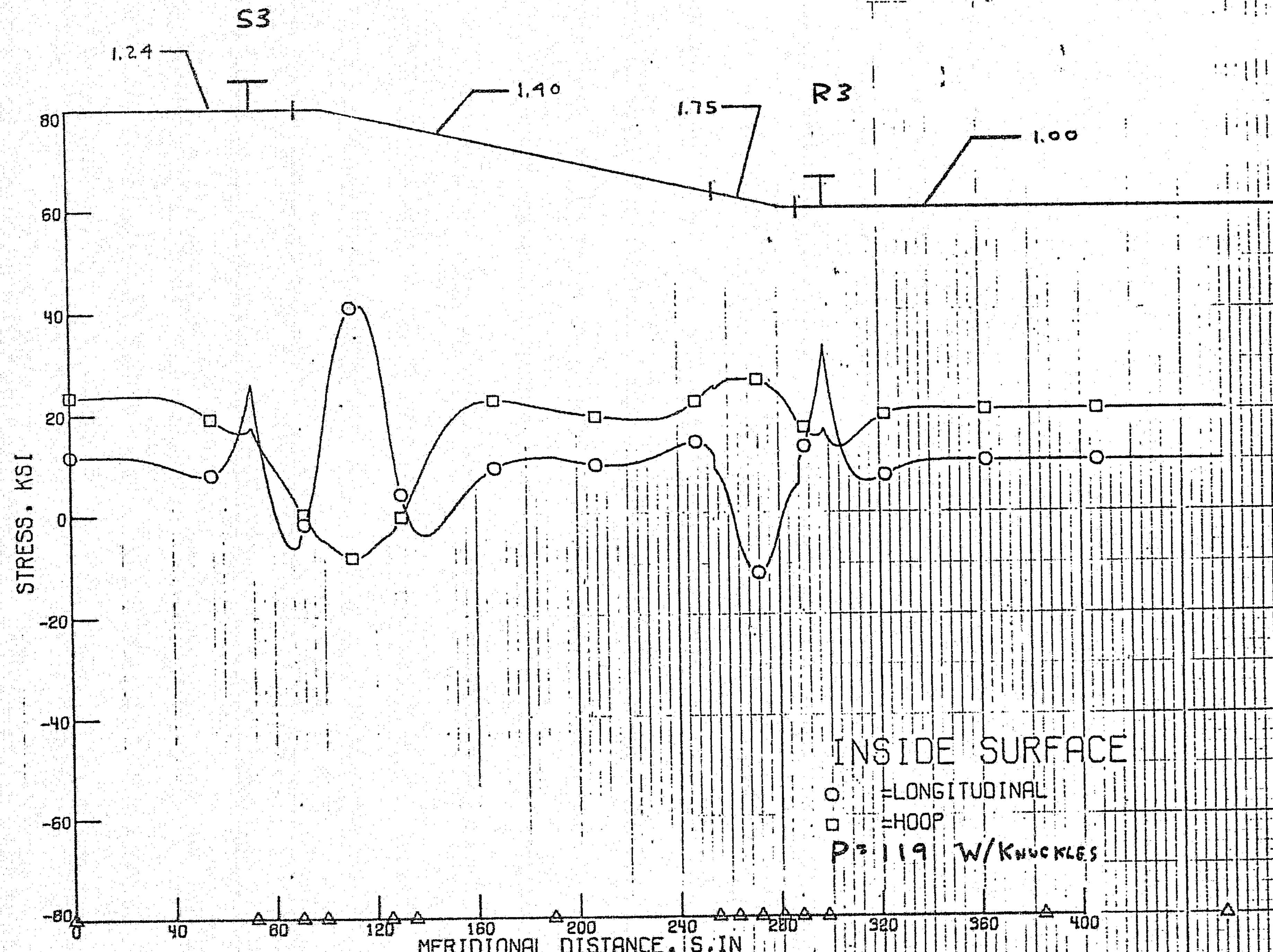

S3
1.24
1.40
1.75
R3
1.00
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE. S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P= 119 W/KNUCKLES

Figure 11

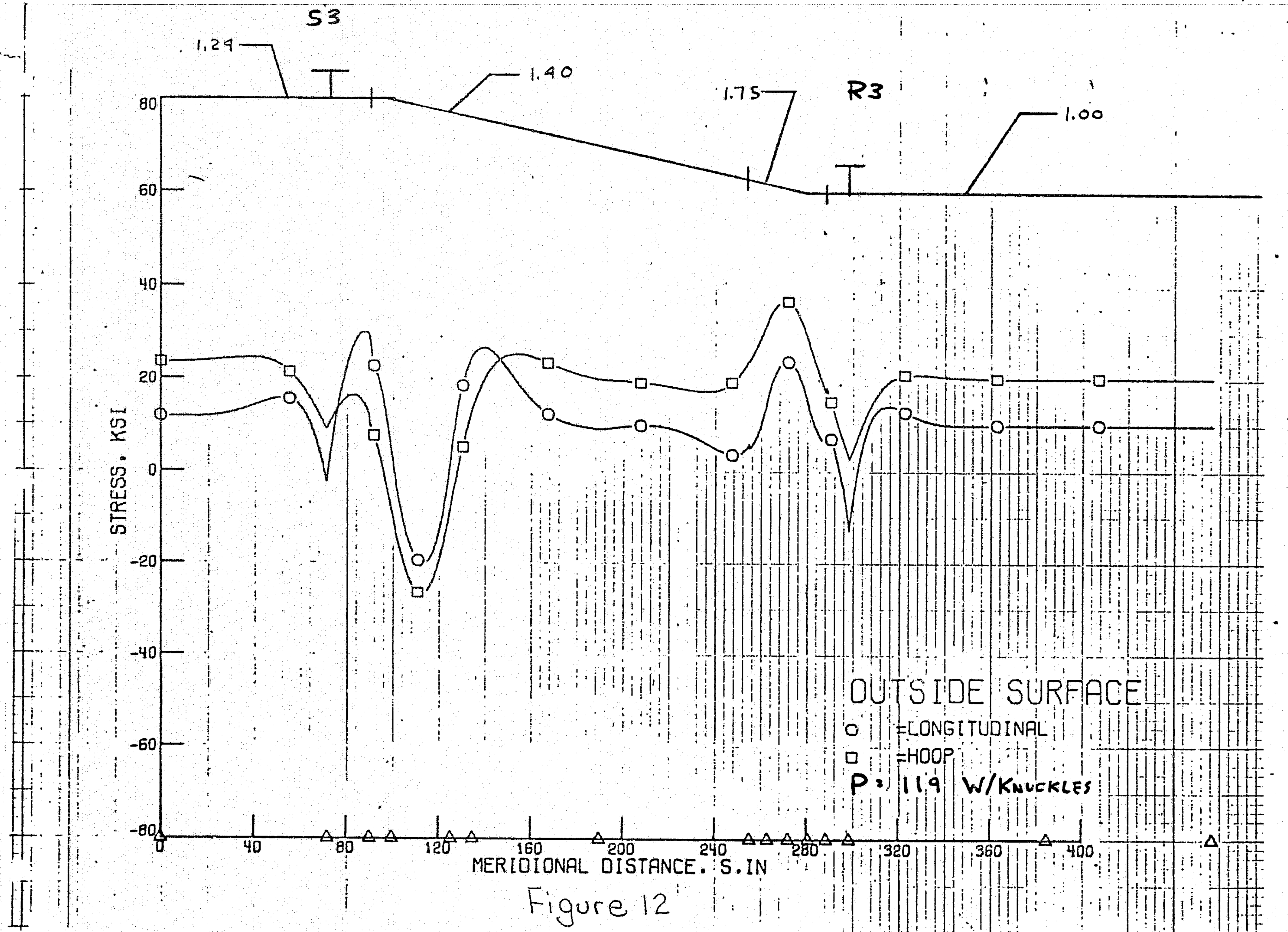

S3
1.29
1.40
1.75
R3
1.00
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE. S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P: 119 W/KNUCKLES

Figure 12

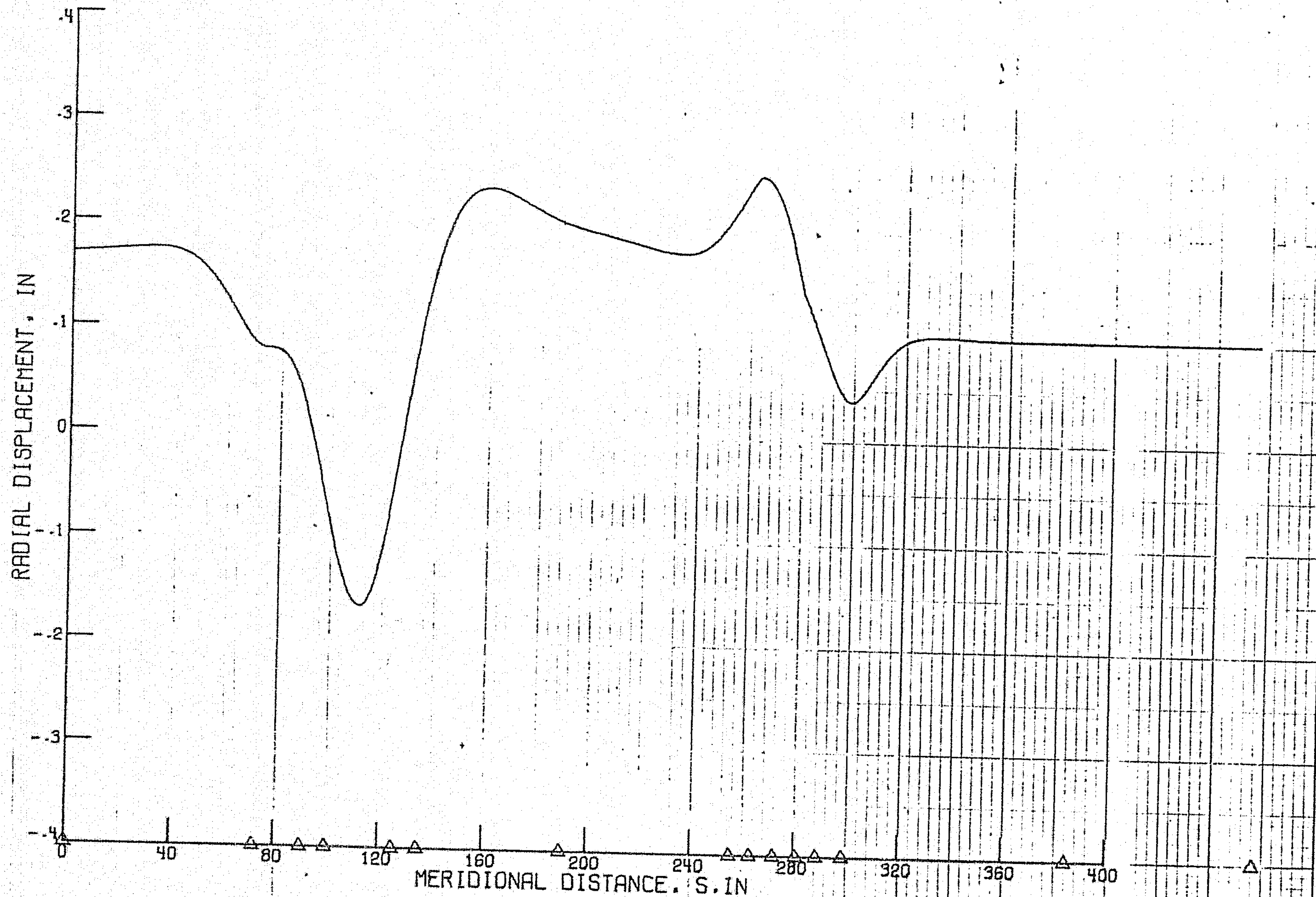

.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
RADIAL DISPLACEMENT, IN
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S, IN

Figure 13

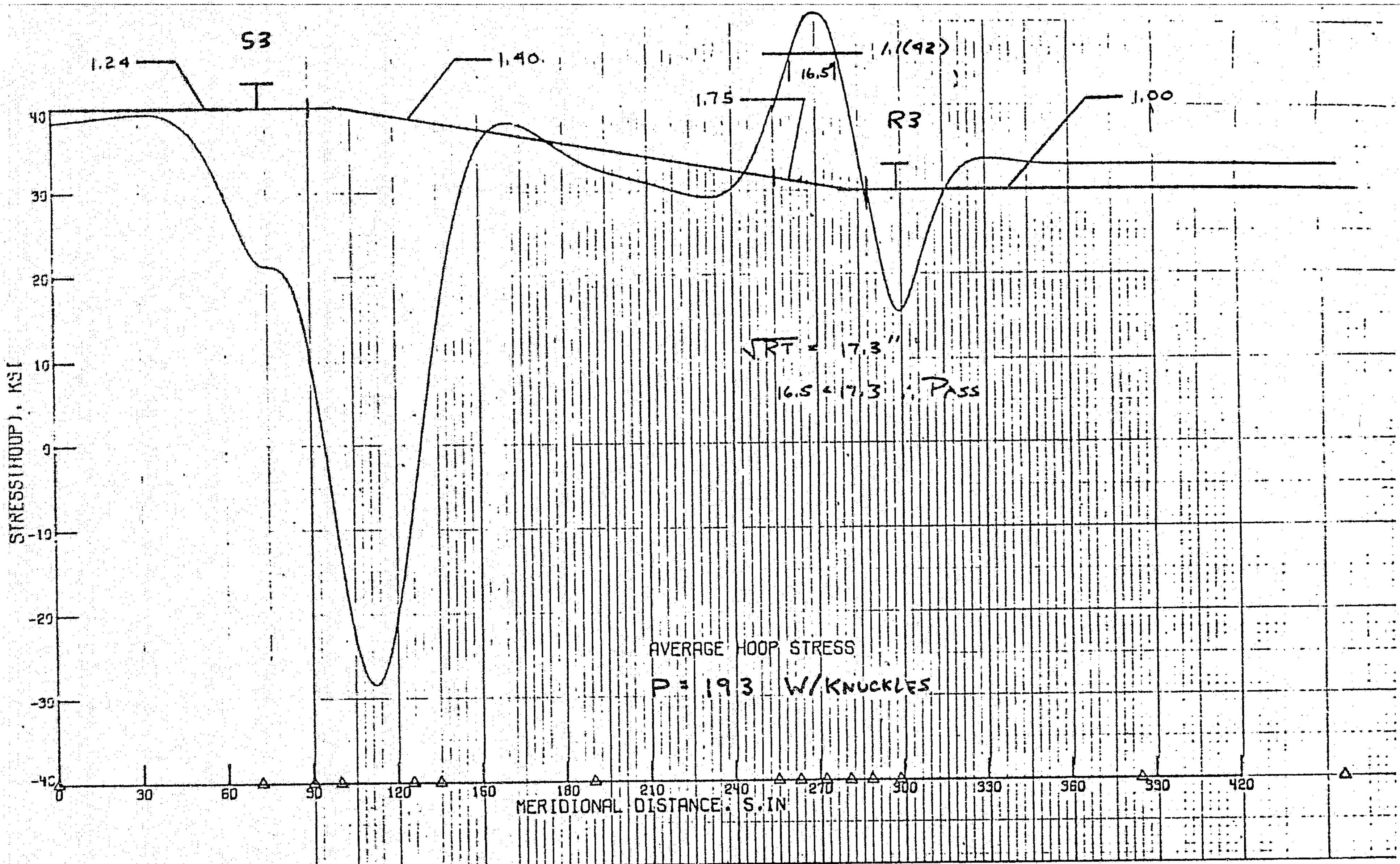

S3
1.24
1.40.
1.75
16.5
1.1(92)
R3
1.00
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
$\sqrt{RT}$ = 17.3"
16.5 < 17.3 ∴ PASS
AVERAGE HOOP STRESS
P = 193 W/KNUCKLES

Figure 14

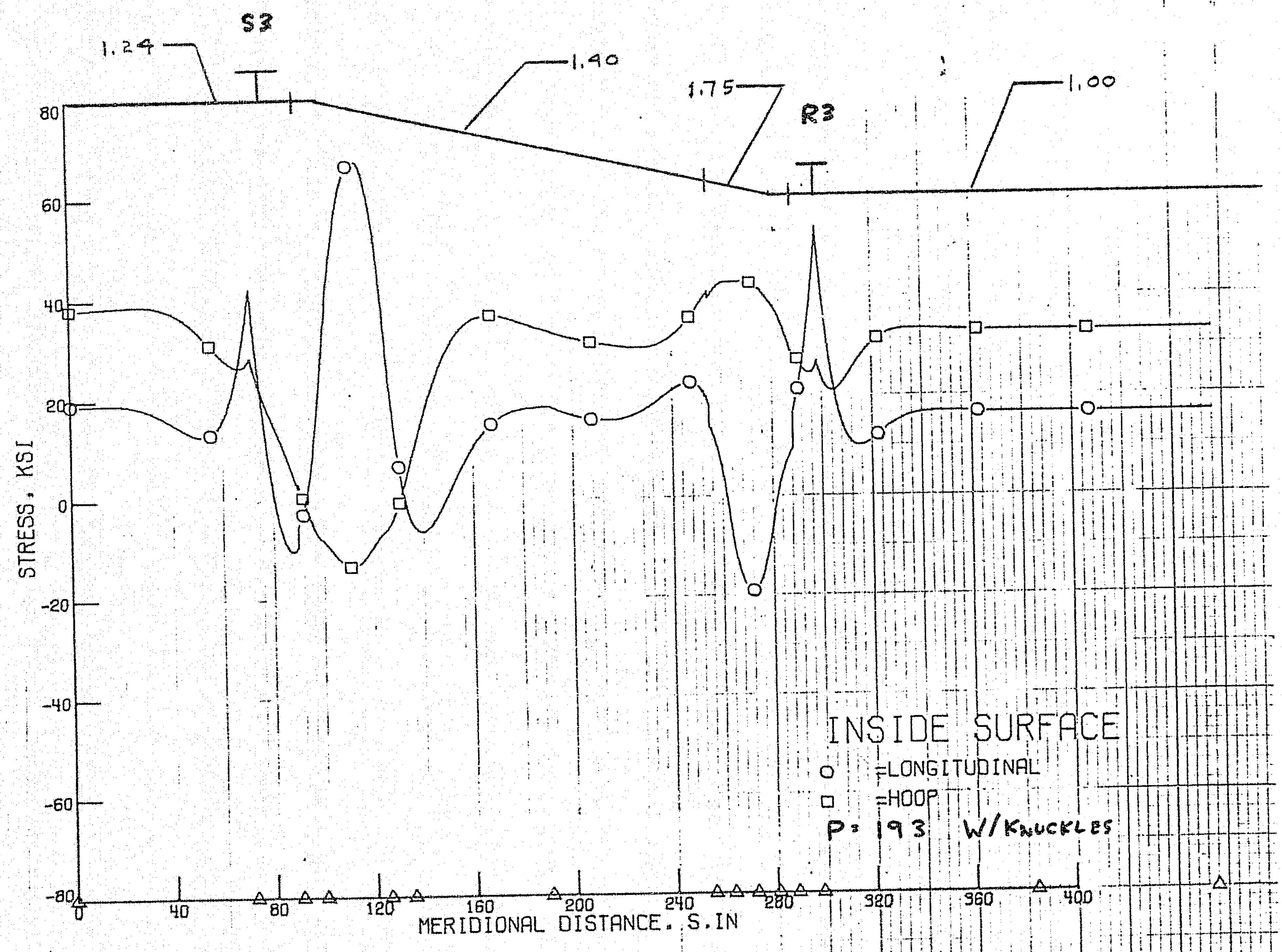

S3
R3
1.24
1.40
1.75
1.00
STRESS, KSI
80
60
40
20
0
-20
-40
-60
-80
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P: 193 W/KNUCKLES

Figure 15

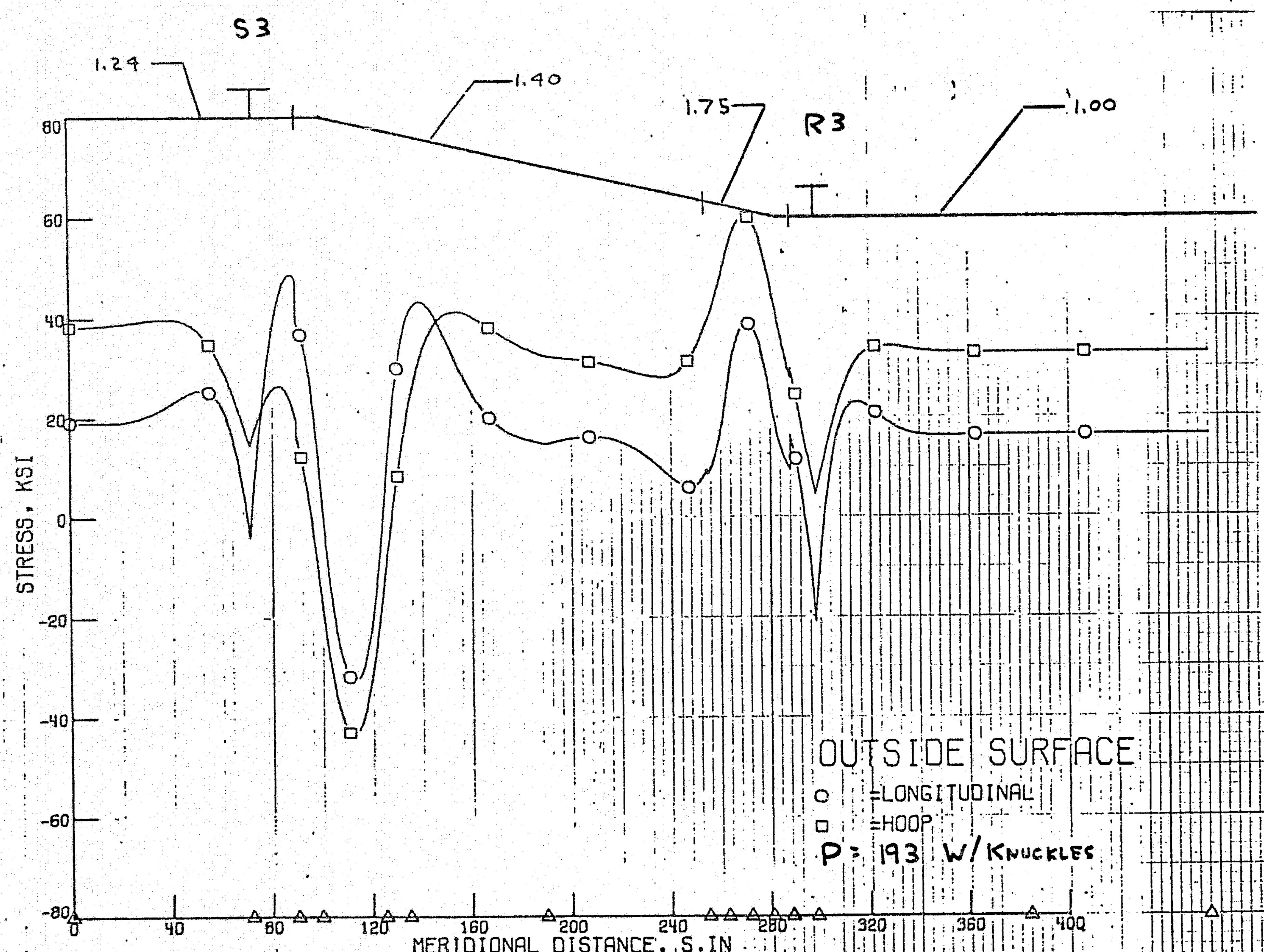

S3
1.24
1.40
1.75
R3
1.00
STRESS, KSI
80
60
40
20
0
-20
-40
-60
-80
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 193 W/KNUCKLES

Figure 16

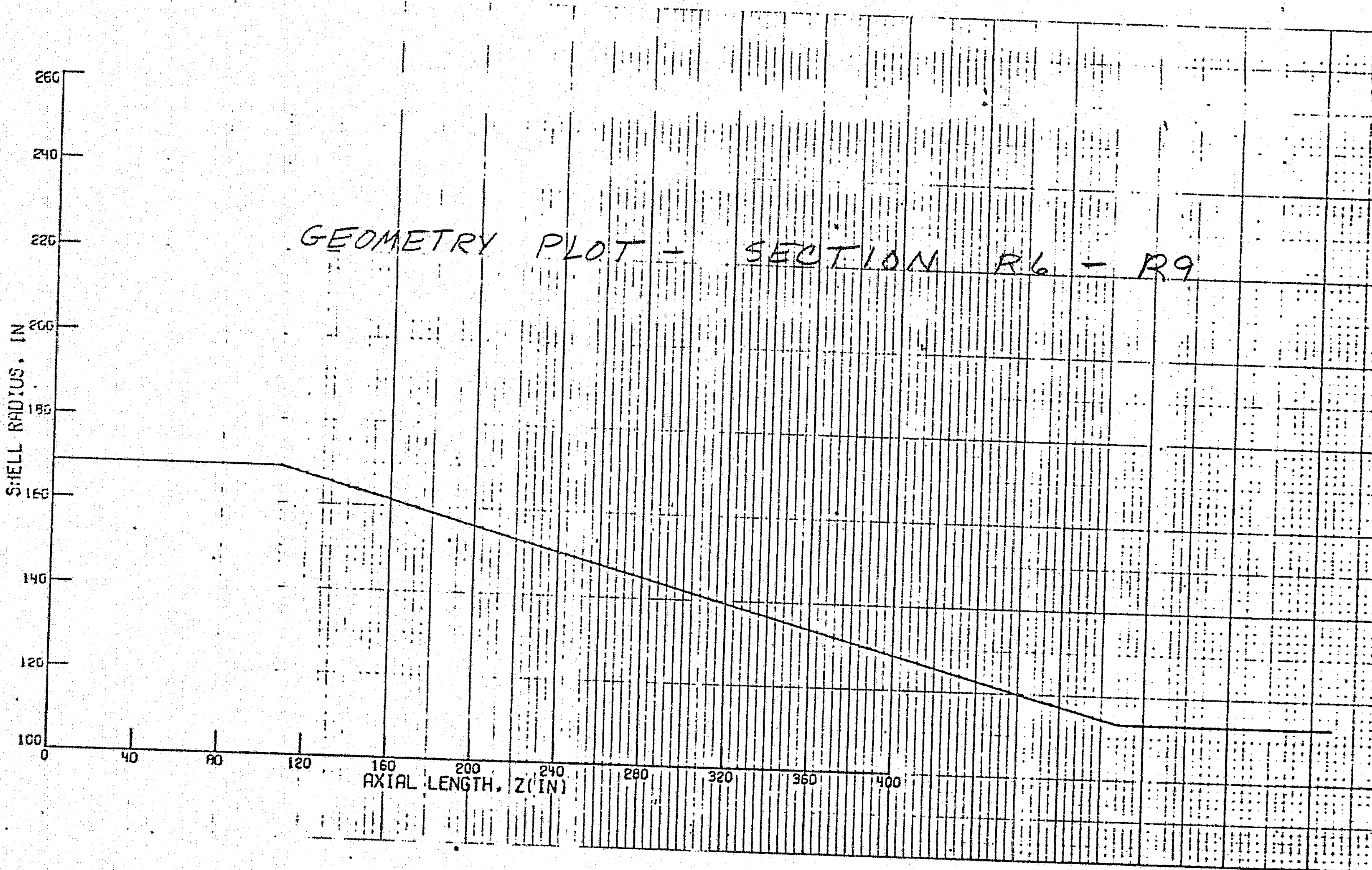

GEOMETRY PLOT - SECTION R6 - R9
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure 17

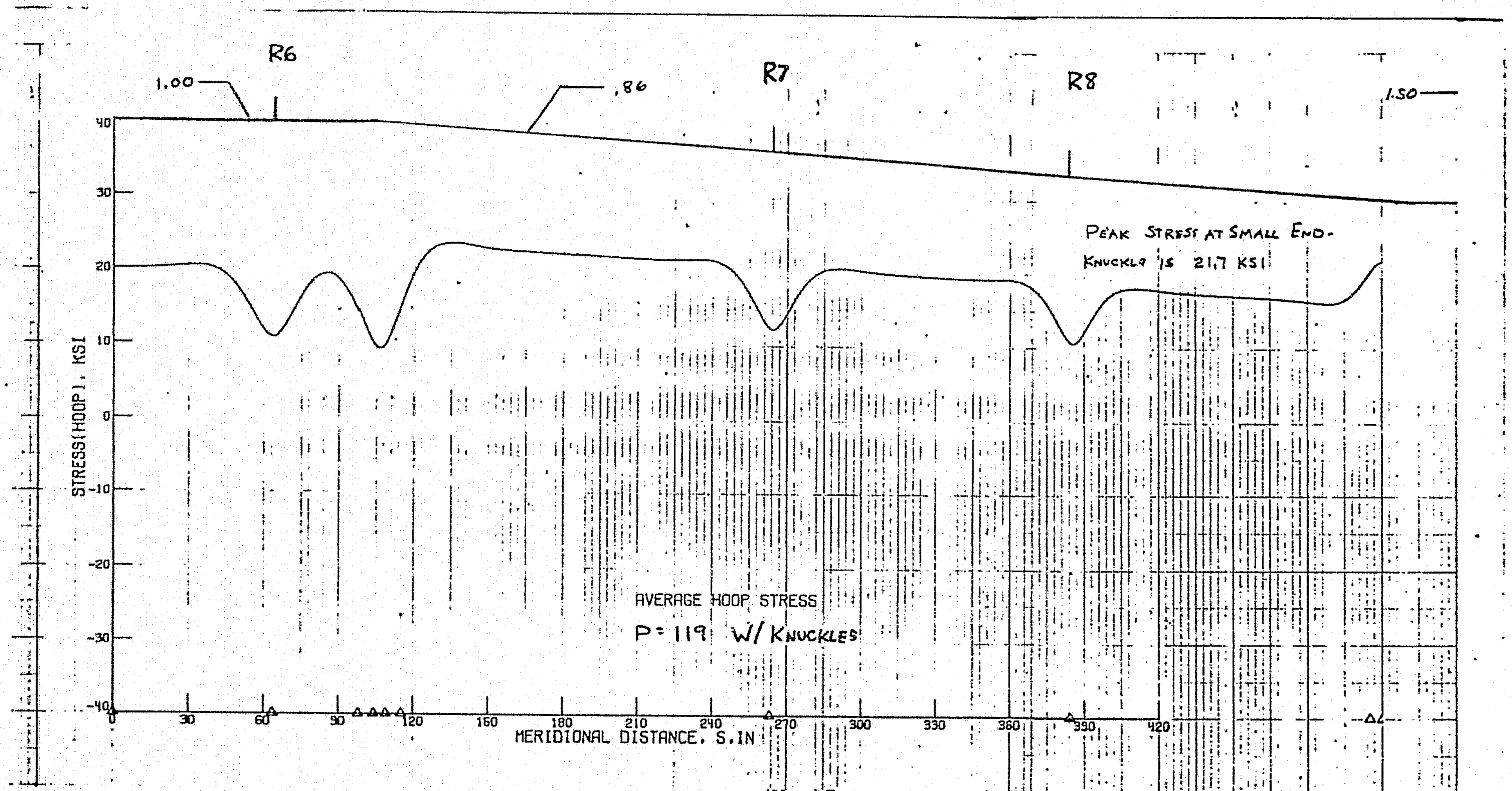

R6
R7
R8
1.00
.86
1.50
PEAK STRESS AT SMALL END-KNUCKLE IS 21.7 KSI
STRESS(HOOP), KSI
AVERAGE HOOP STRESS
P = 119 W/KNUCKLES
MERIDIONAL DISTANCE, S.IN

Figure 18

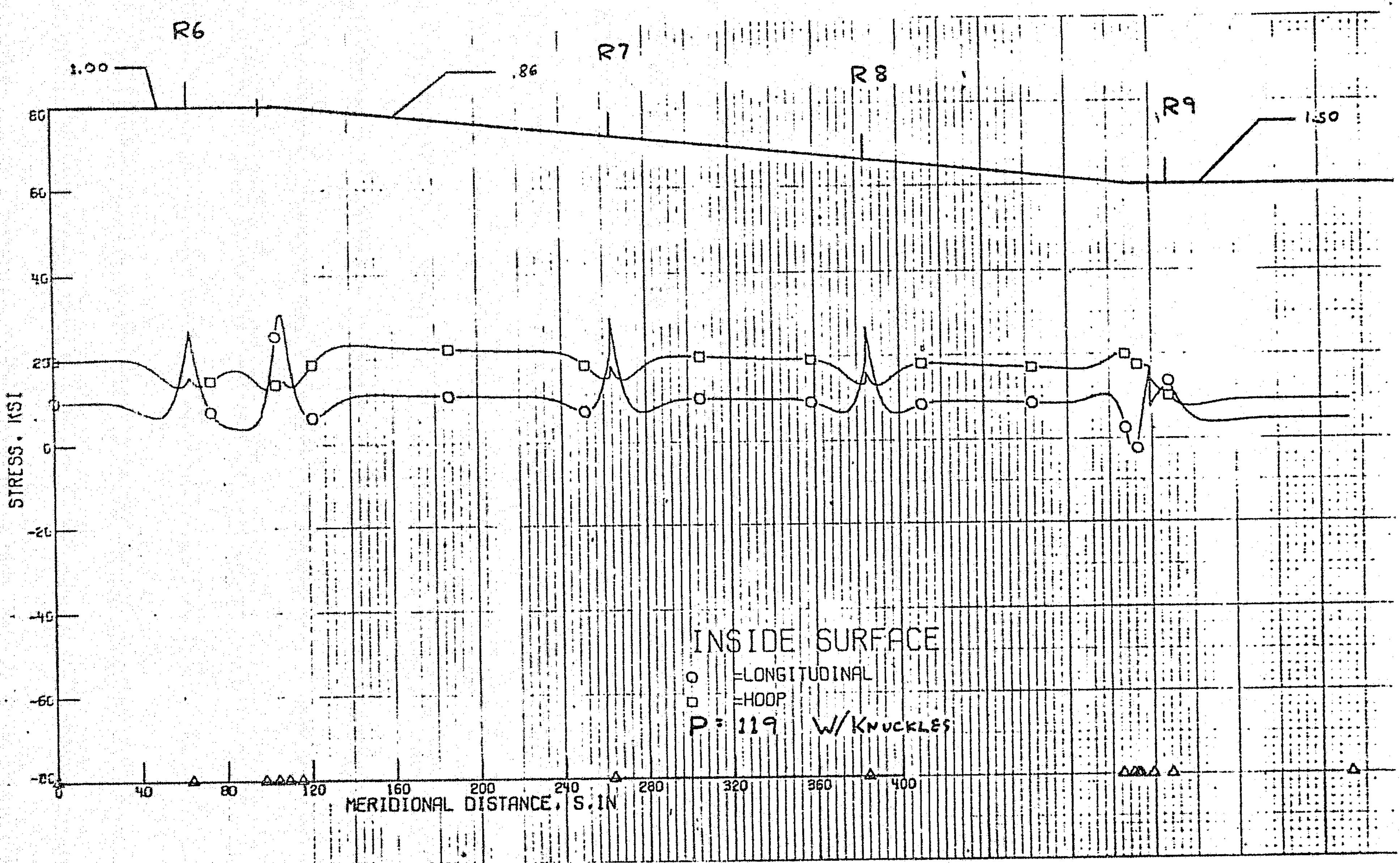

R6
R7
R8
R9
1.00
.86
1.50
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 119 W/KNUCKLES

Figure 19

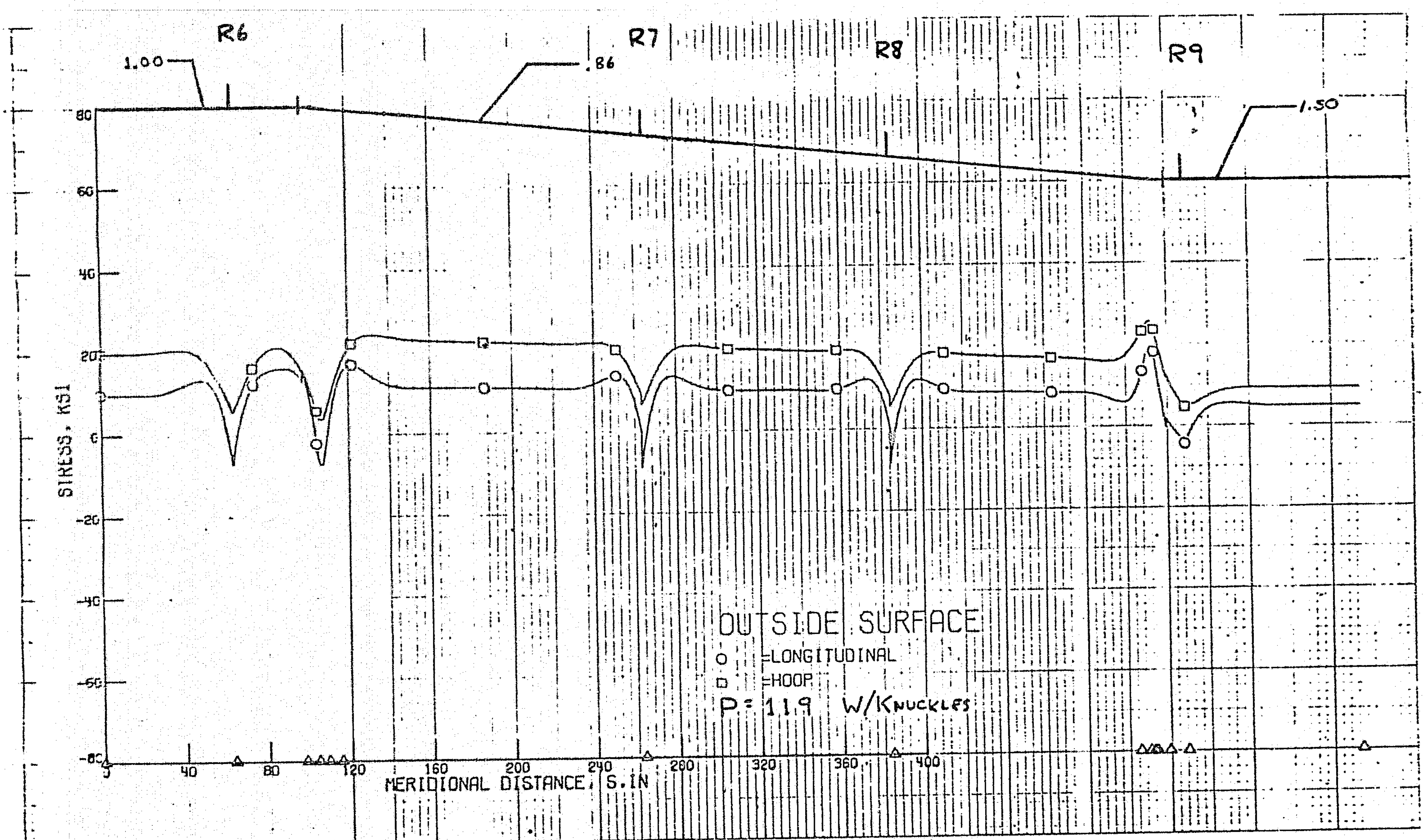

R6
R7
R8
R9
1.00
.86
1.50
STRESS, KSI
80
60
40
20
0
-20
-40
-60
-80
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 11.9 W/Knuckles

Figure 20

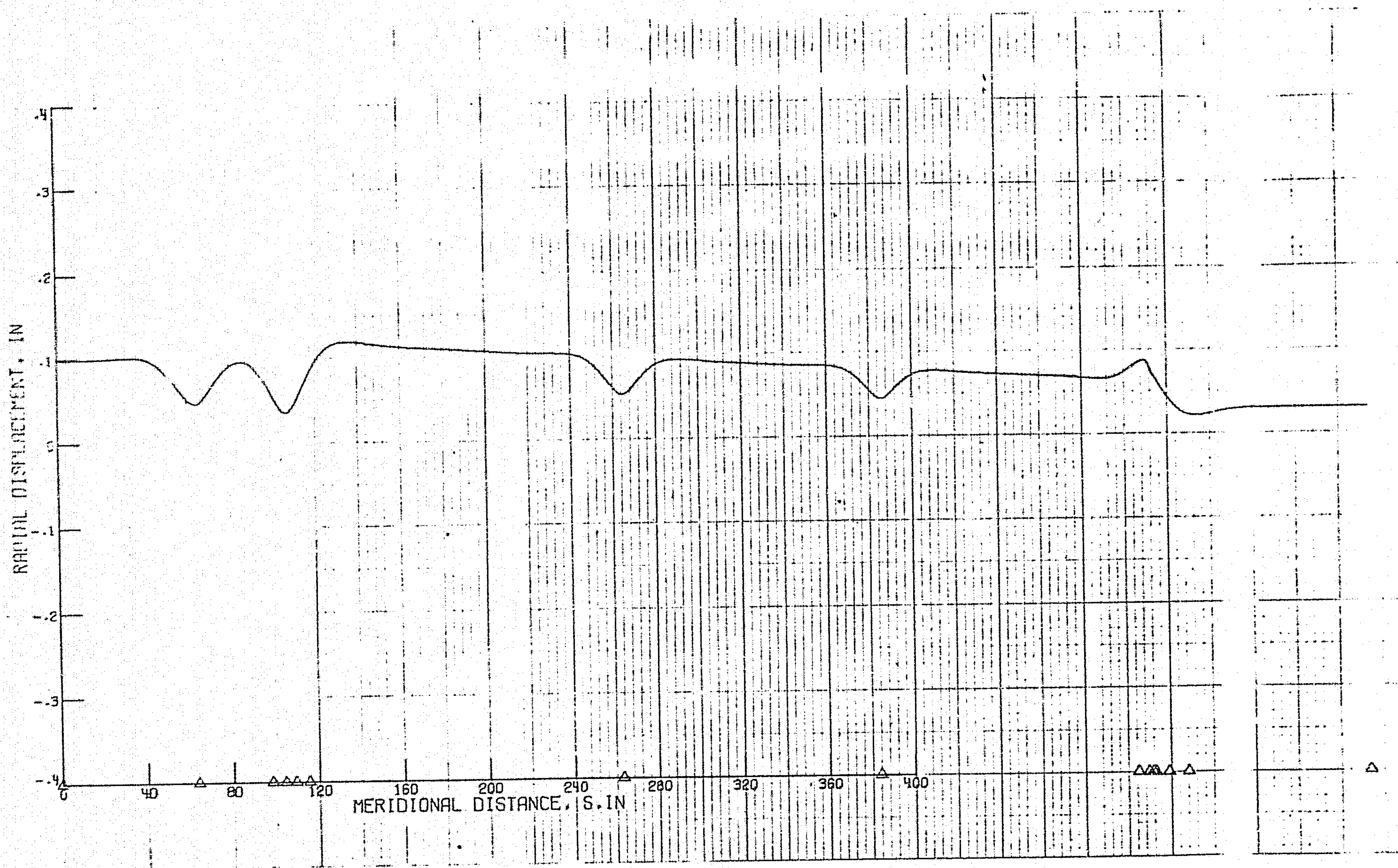

RADIAL DISPLACEMENT, IN
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN

Figure 21

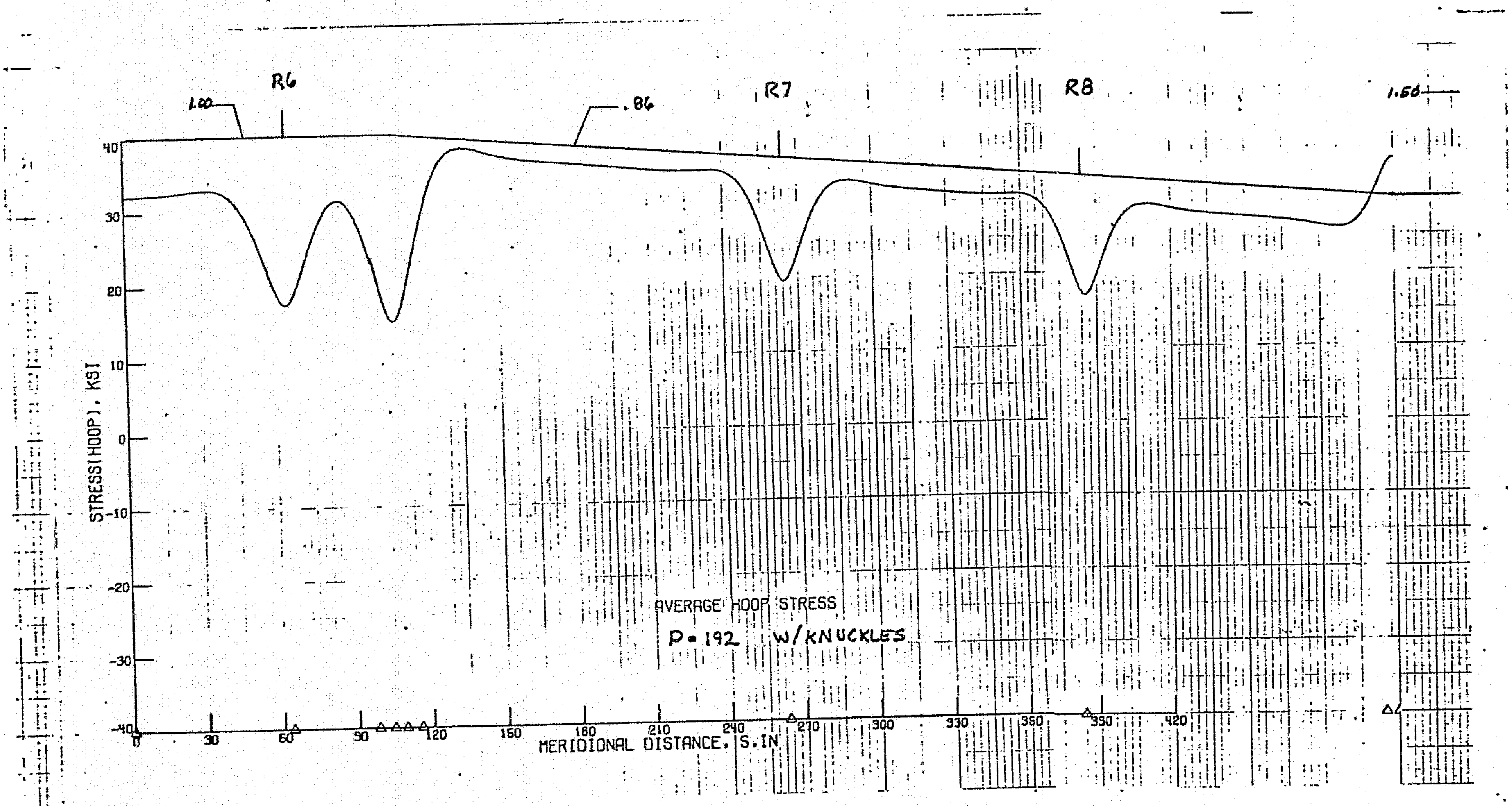

R6
R7
R8
1.00
.86
1.50
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
AVERAGE HOOP STRESS
P = 192 W/KNUCKLES

Figure 22

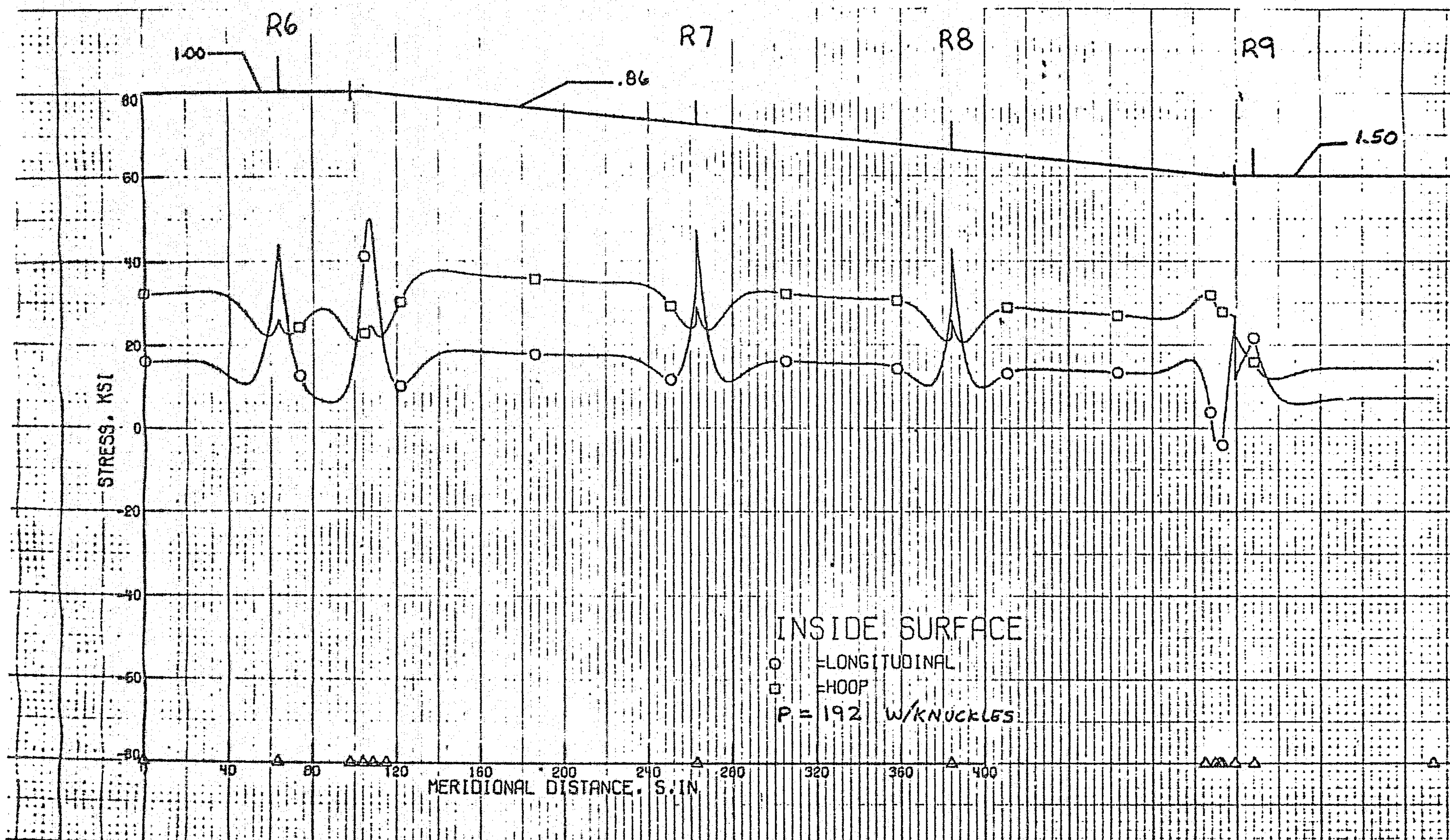

R6
R7
R8
R9
1.00
.86
1.50
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 192 W/KNUCKLES

Figure 23

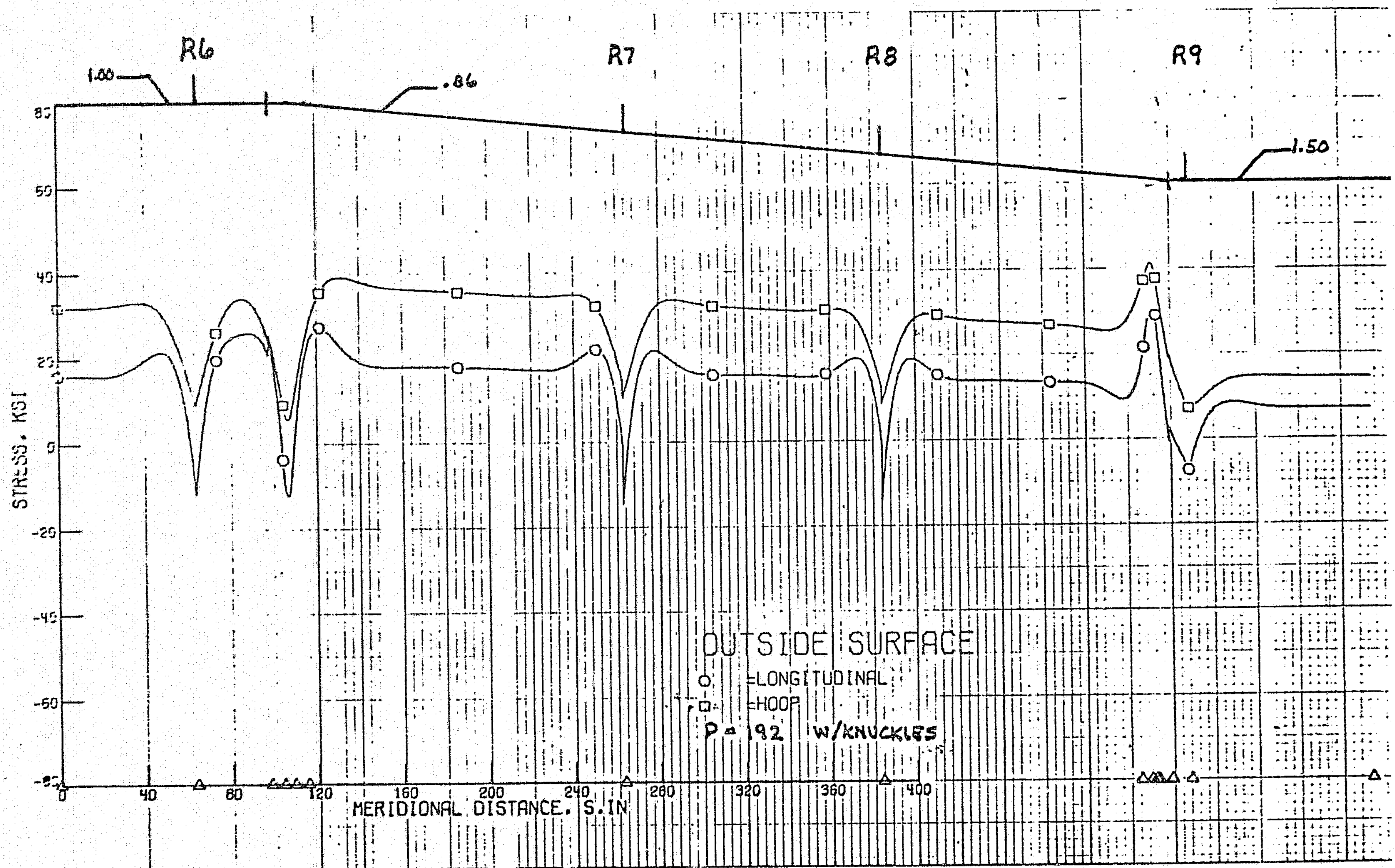

R6
R7
R8
R9
1.00
.86
1.50
STRESS, KSI
MERIDIONAL DISTANCE, S, IN
OUTSIDE SURFACE
=LONGITUDINAL
=HOOP
P = 192 W/KNUCKLES

Figure 24

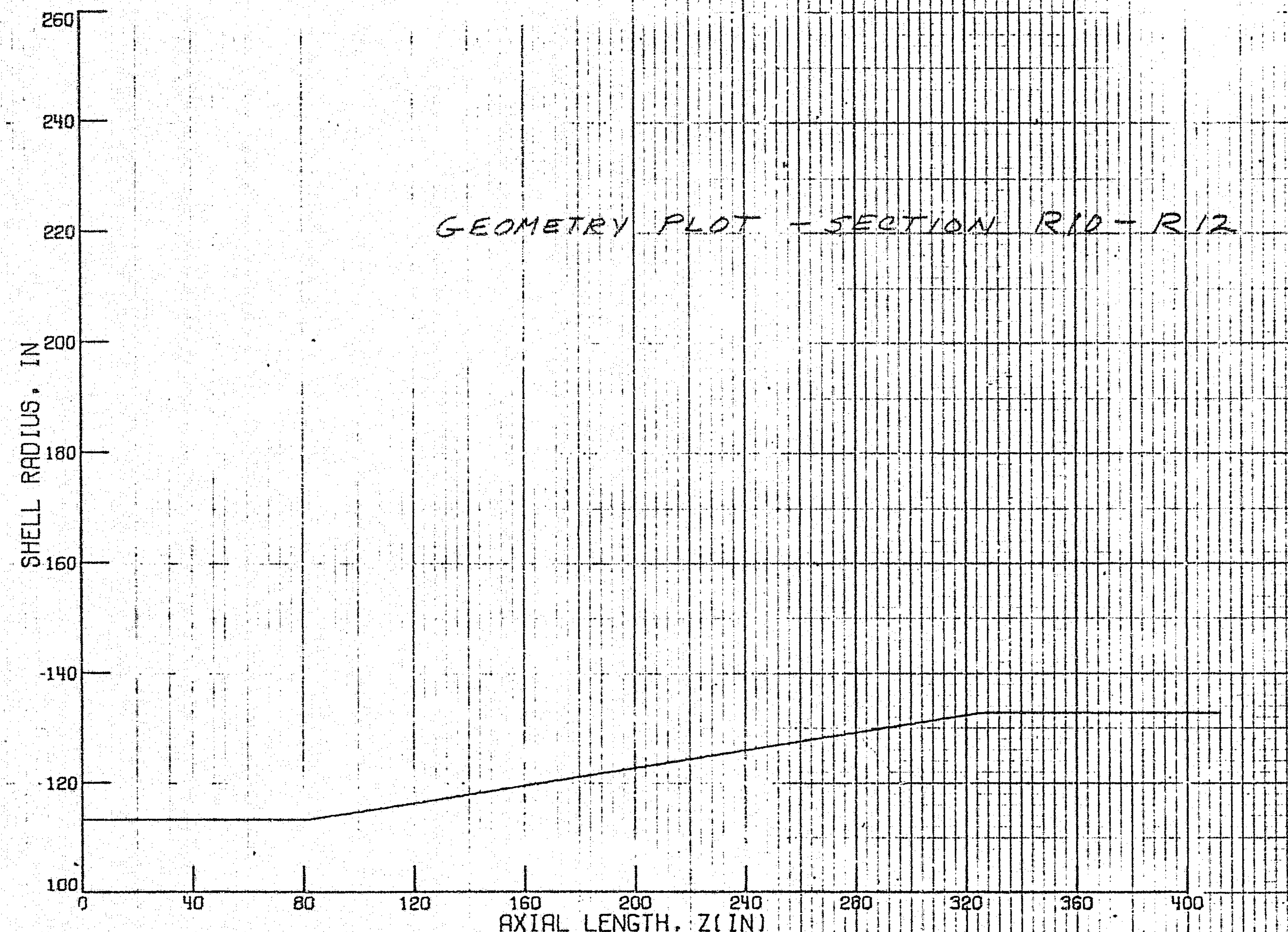

GEOMETRY PLOT - SECTION R10 - R12
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure 25

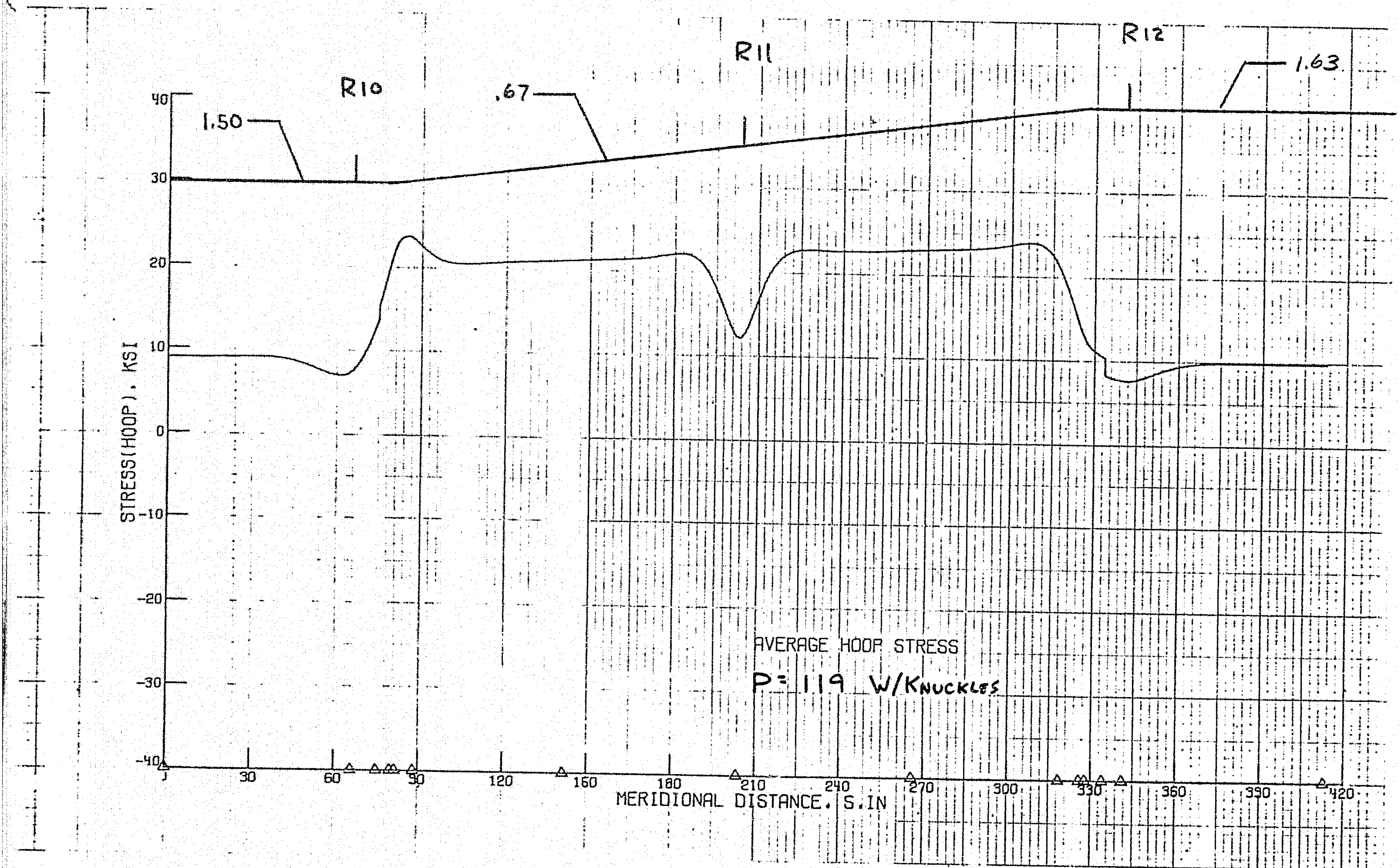

R10
R11
R12
1.50
.67
1.63
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
30
60
90
120
160
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
AVERAGE HOOP STRESS
P= 119 W/KNUCKLES

Figure 26

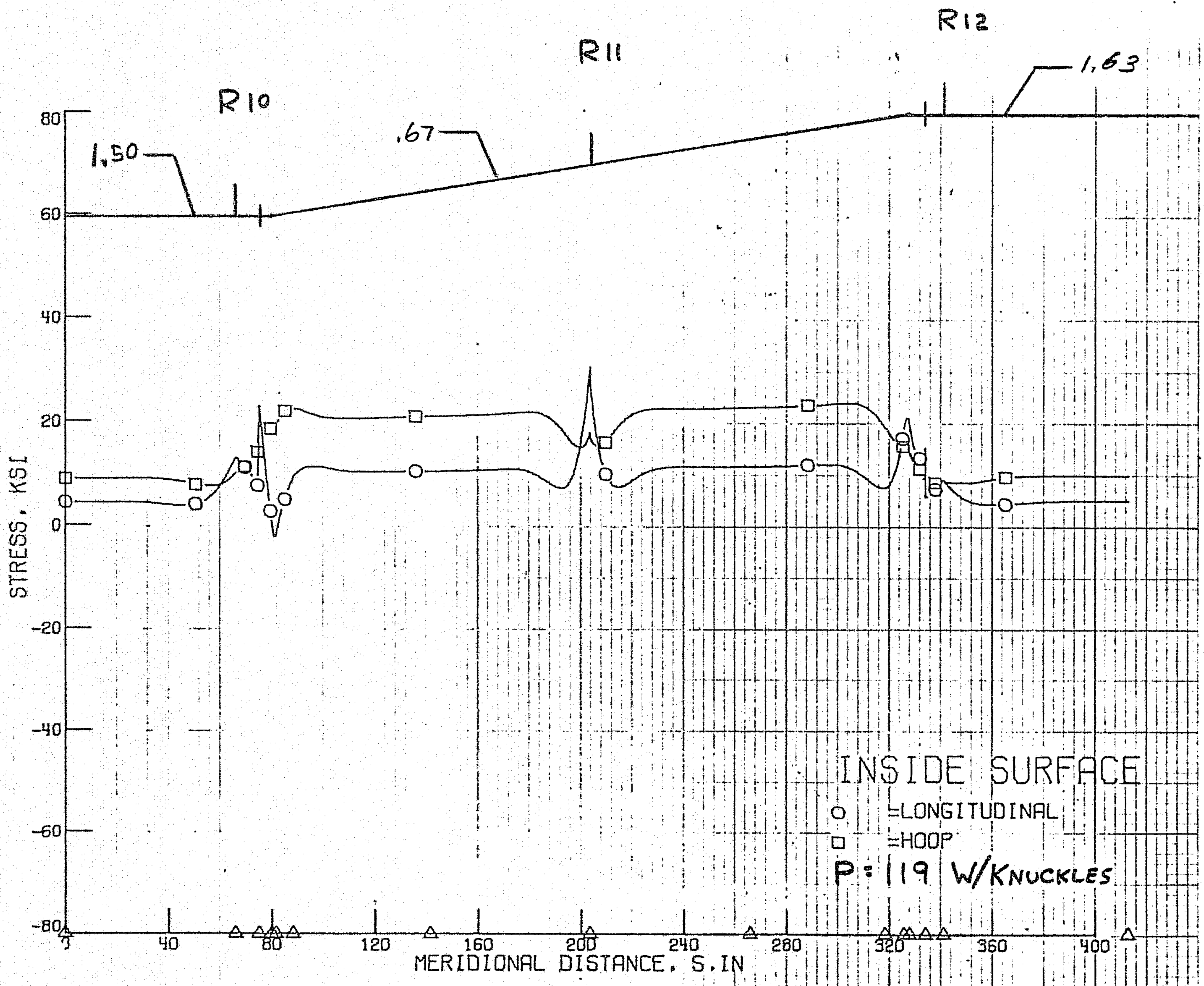

R10
R11
R12
1,50
.67
1,63
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P: 119 W/KNUCKLES

Figure 27

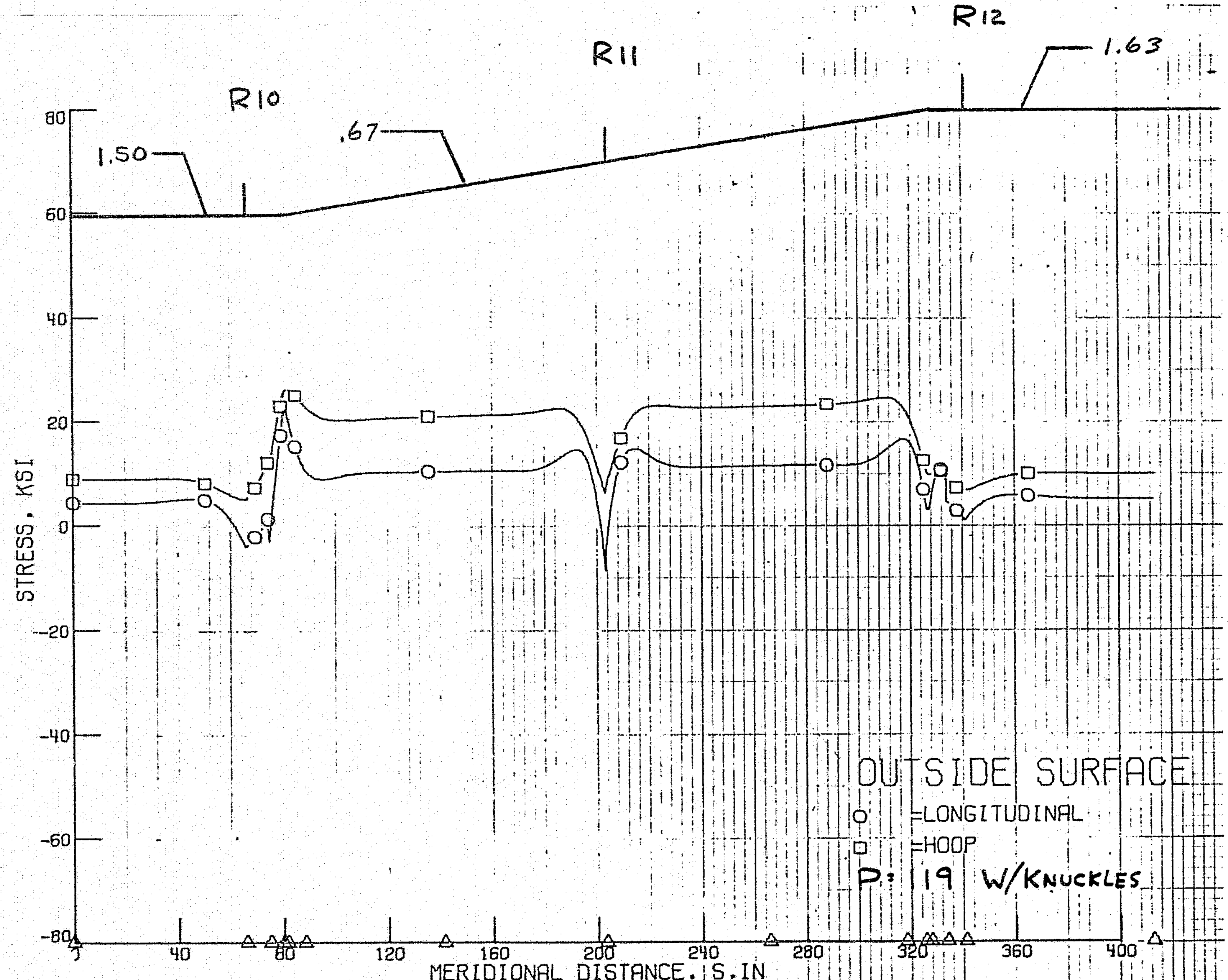
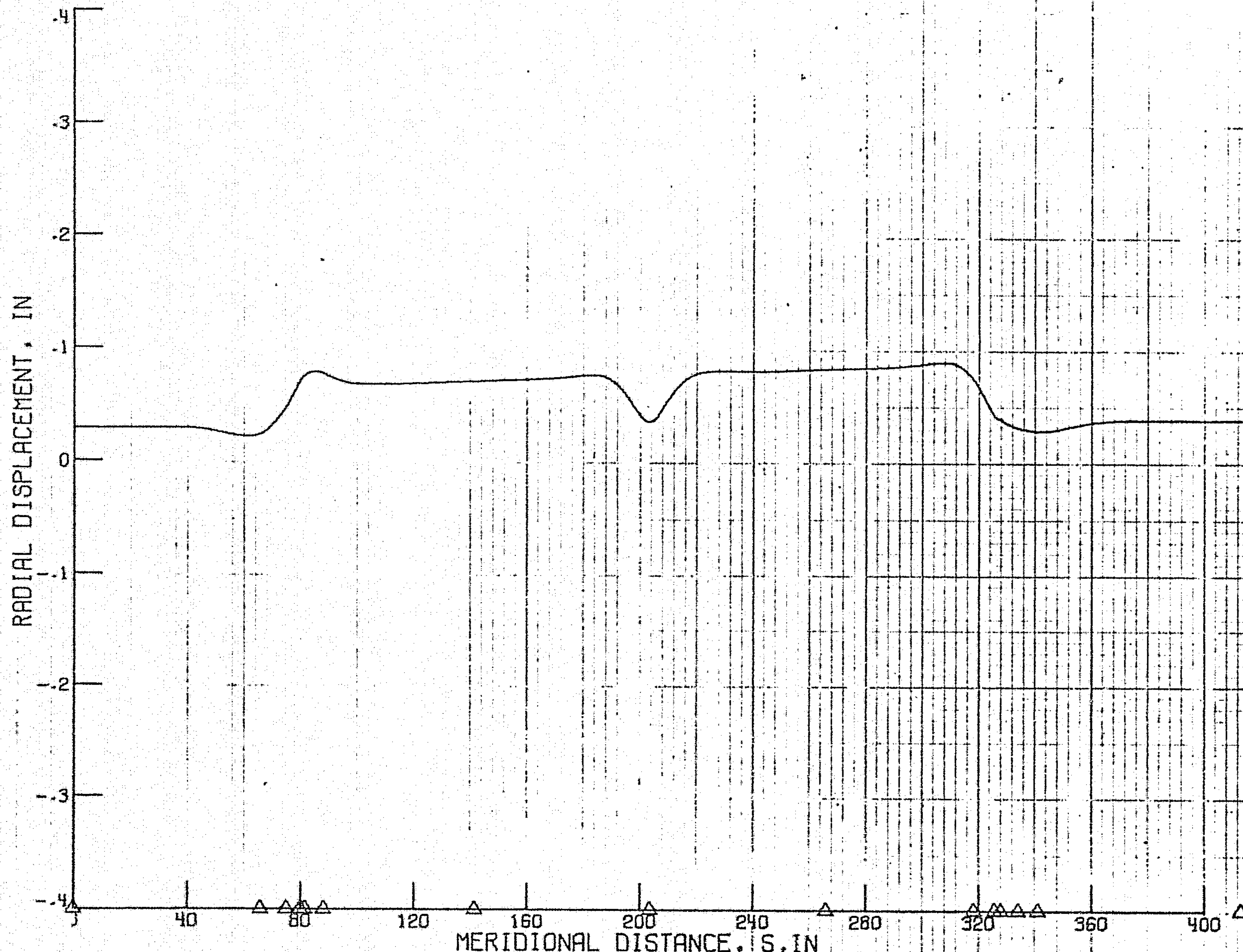

R10
R11
R12
1.50
.67
1.63
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P: 19 W/KNUCKLES

Figure 28



RADIAL DISPLACEMENT, IN
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN

Figure 29

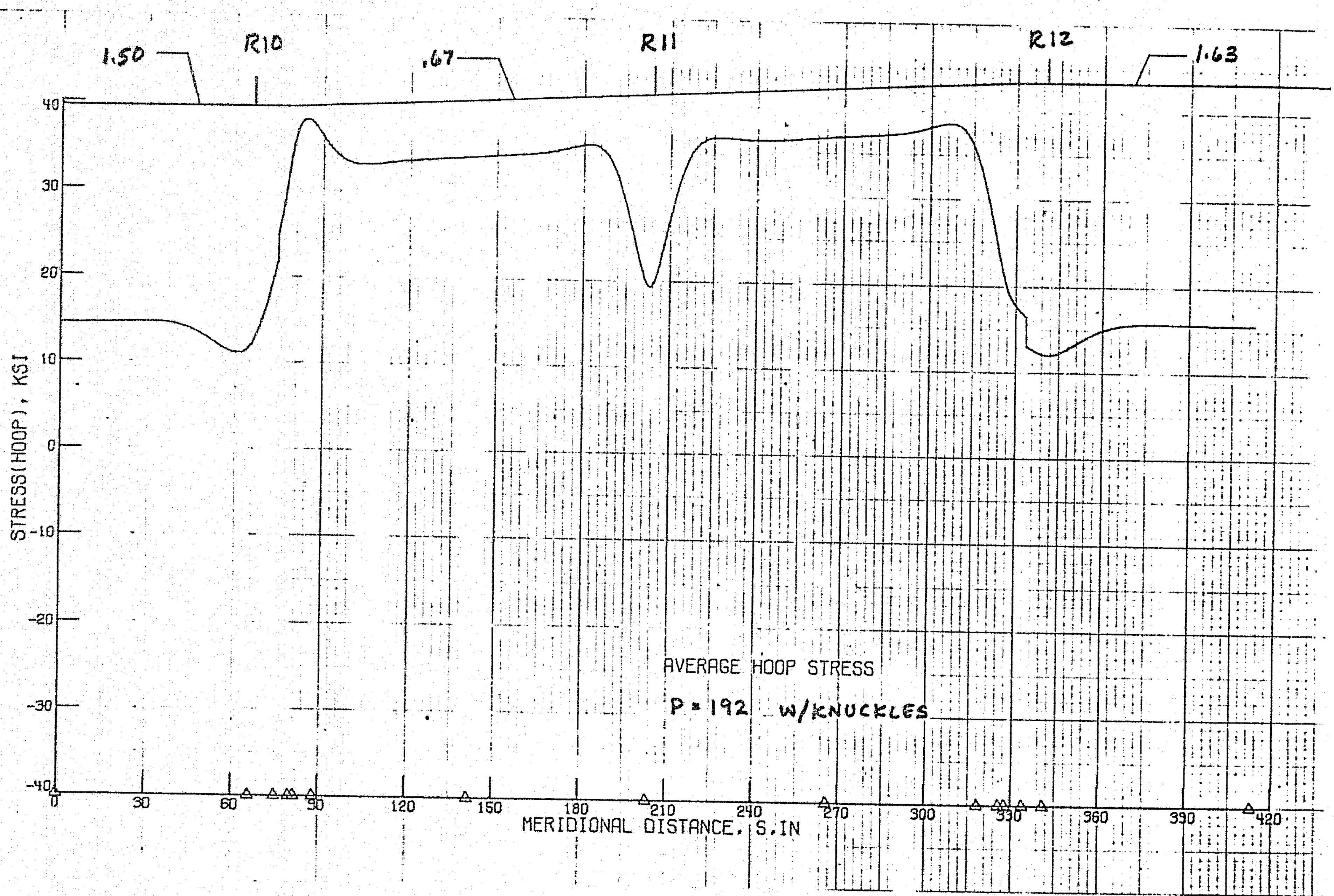

1.50
R10
.67
R11
R12
1.63
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
AVERAGE HOOP STRESS
P = 192 W/KNUCKLES

Figure 30

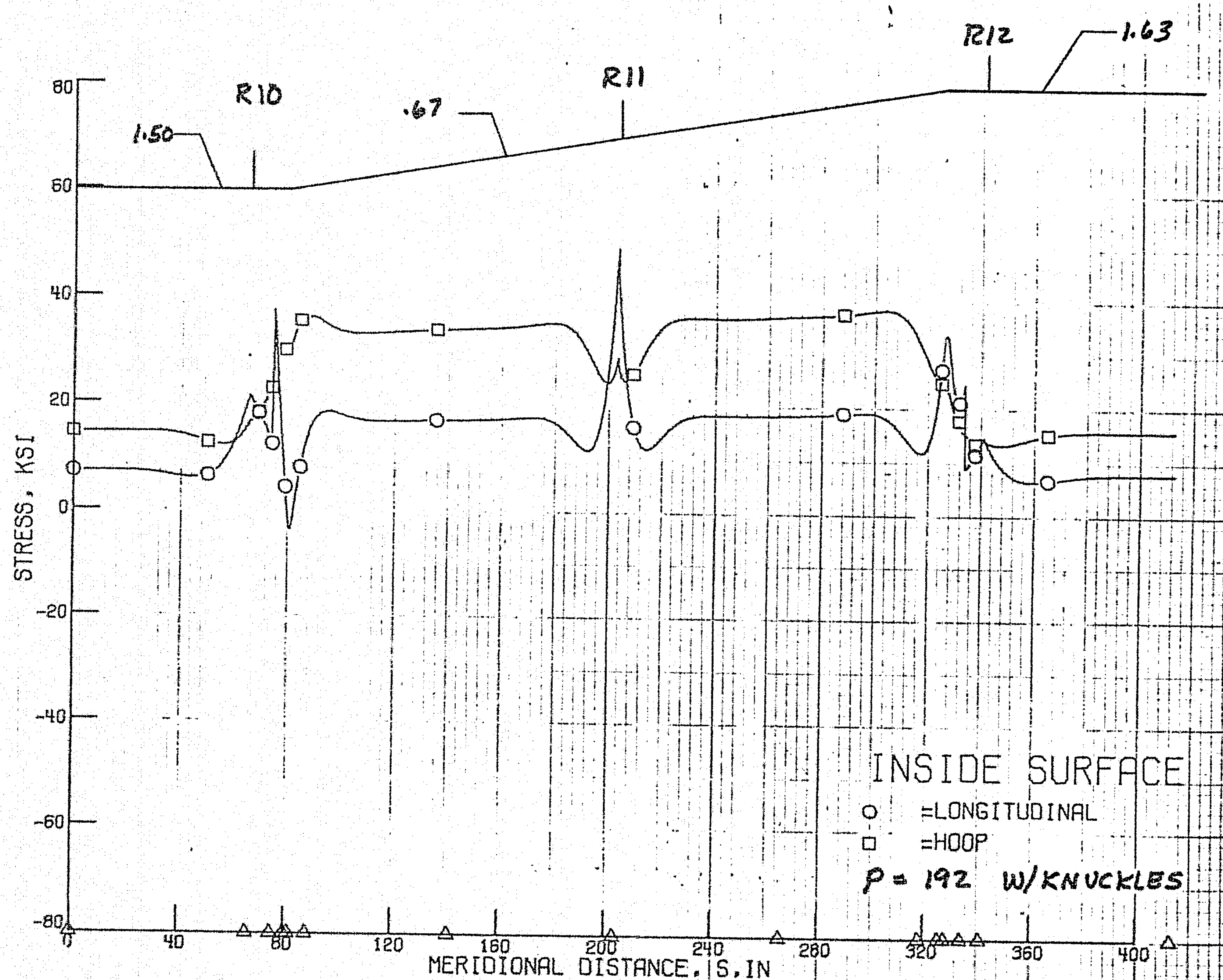

R10
R11
R12
1.50
.67
1.63
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 192 W/KNUCKLES

Figure 31

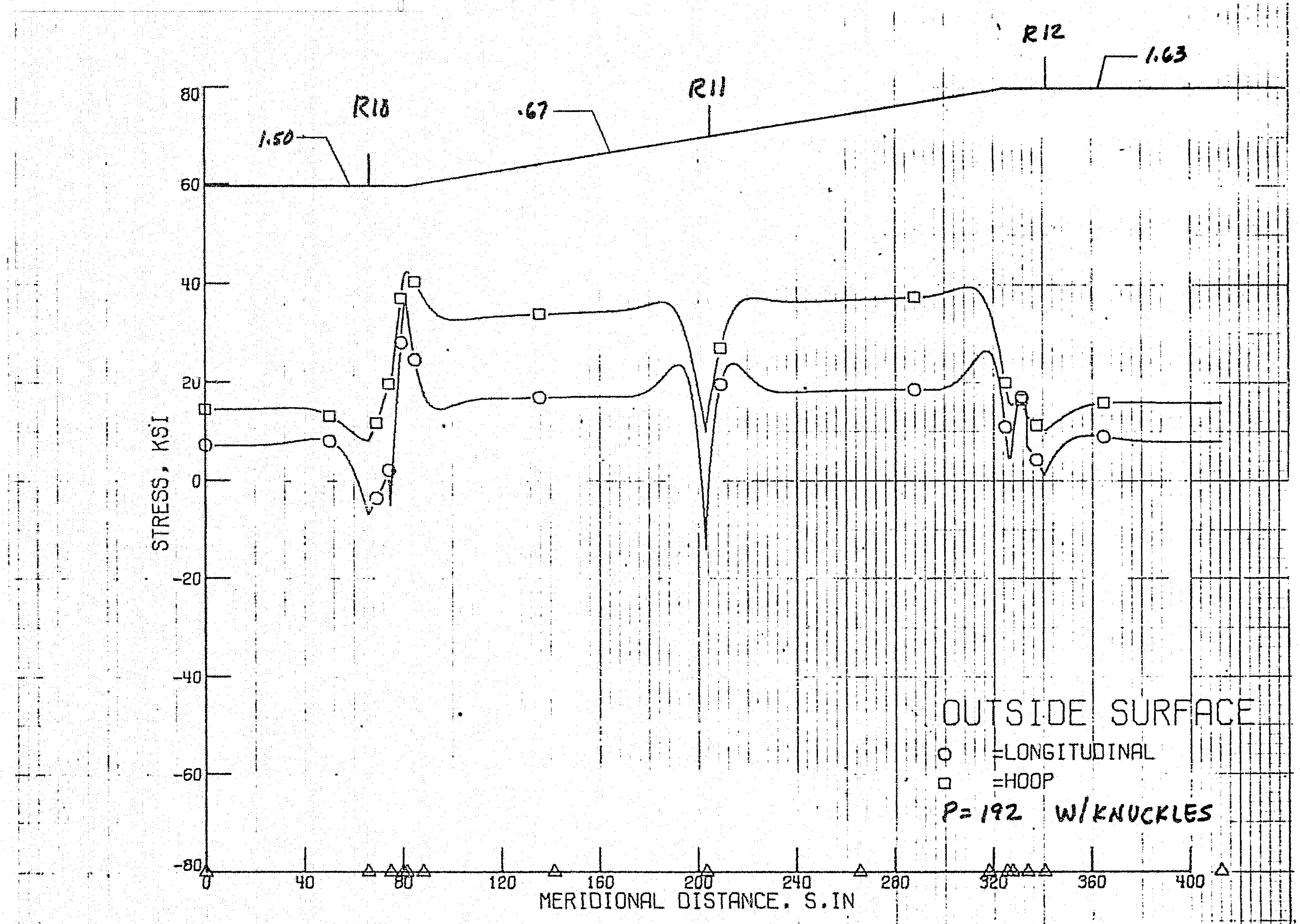
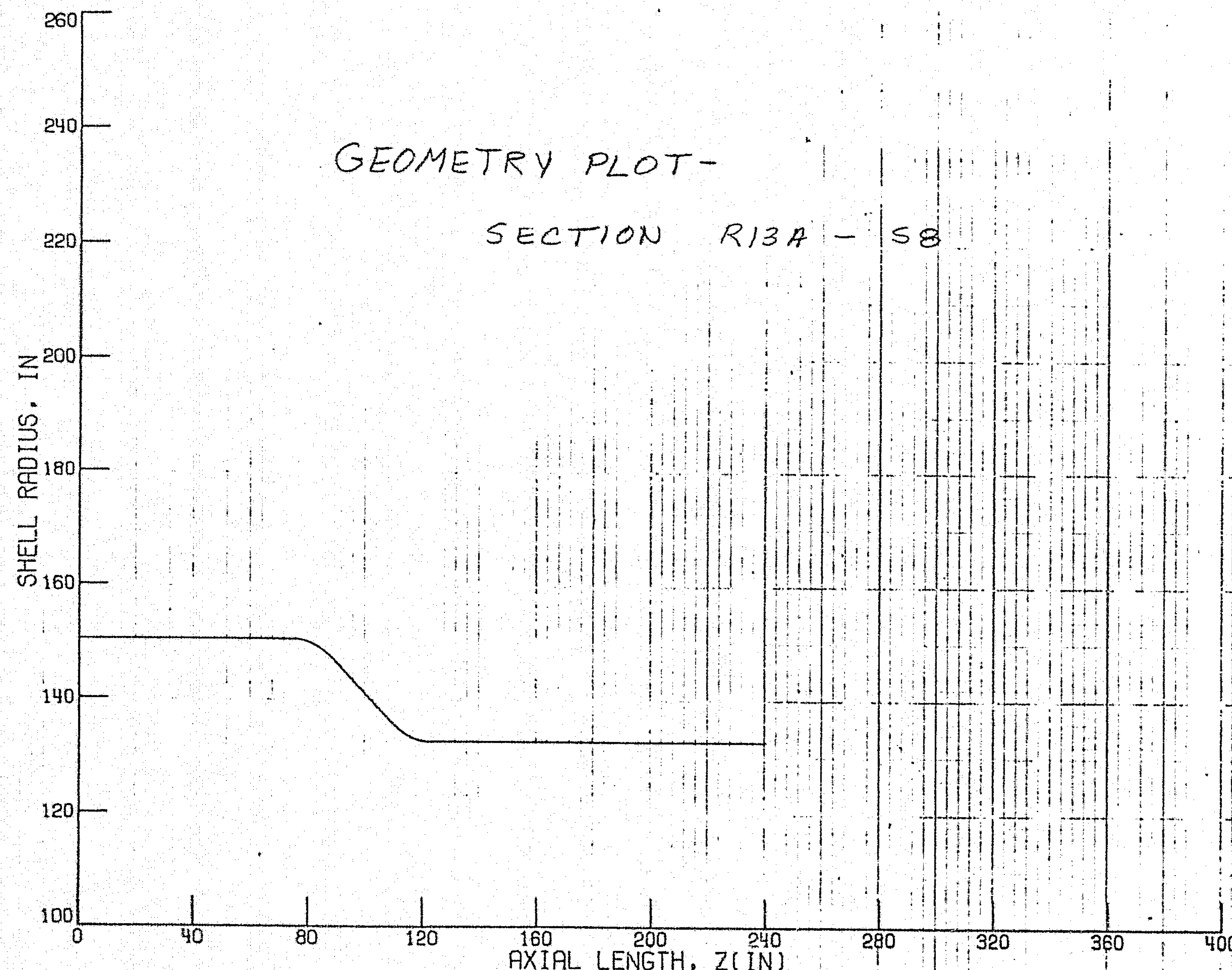

R12
1.63
R11
R10
.67
1.50
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P= 192 W/KNUCKLES

Figure 32


GEOMETRY PLOT-
SECTION R13A - S8
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure

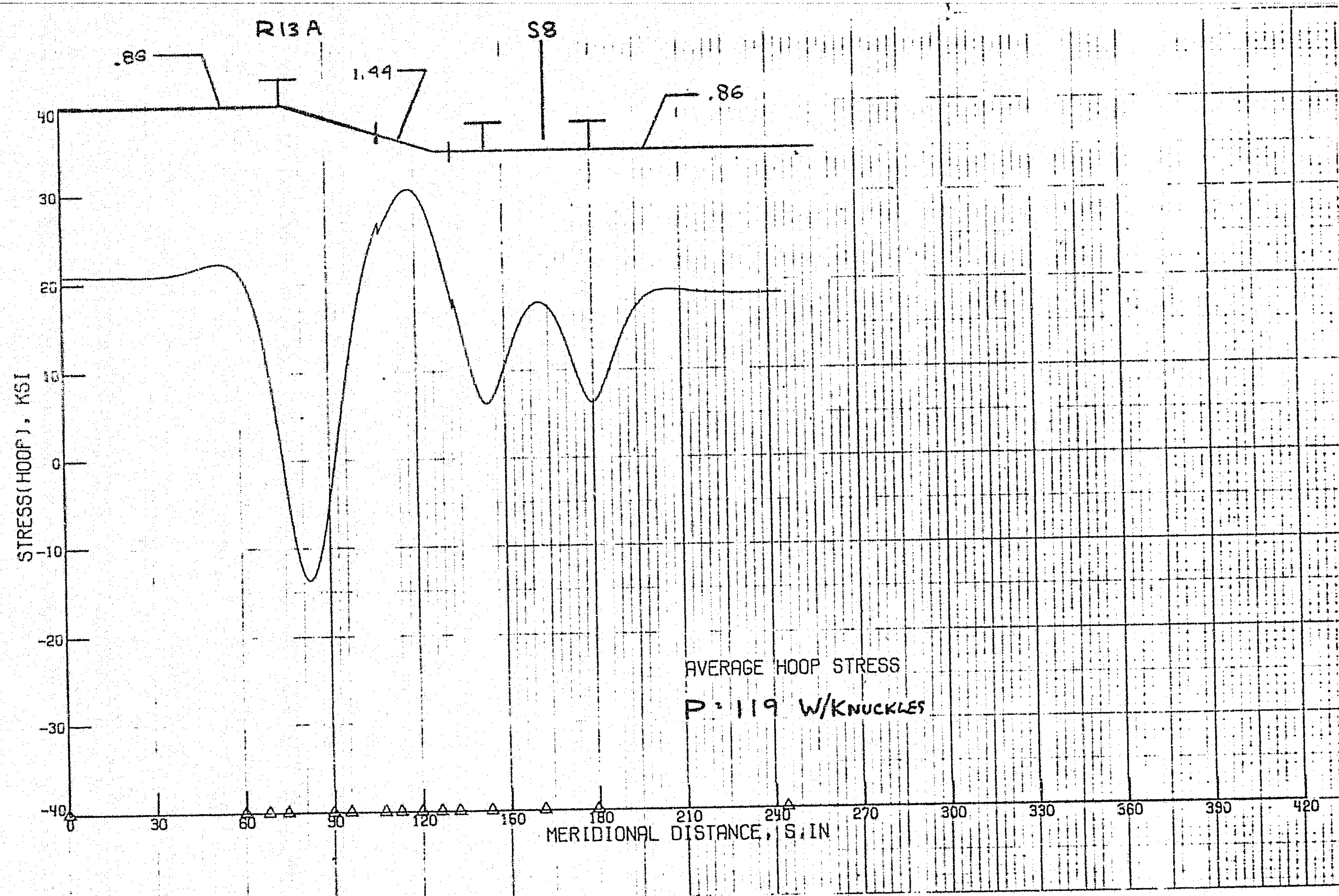

R13A
S8
.89
1.44
.86
40
30
20
10
0
-10
-20
-30
-40
STRESS(HOOP), KSI
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S,IN
AVERAGE HOOP STRESS
P: 119 W/KNUCKLES

Figure 34

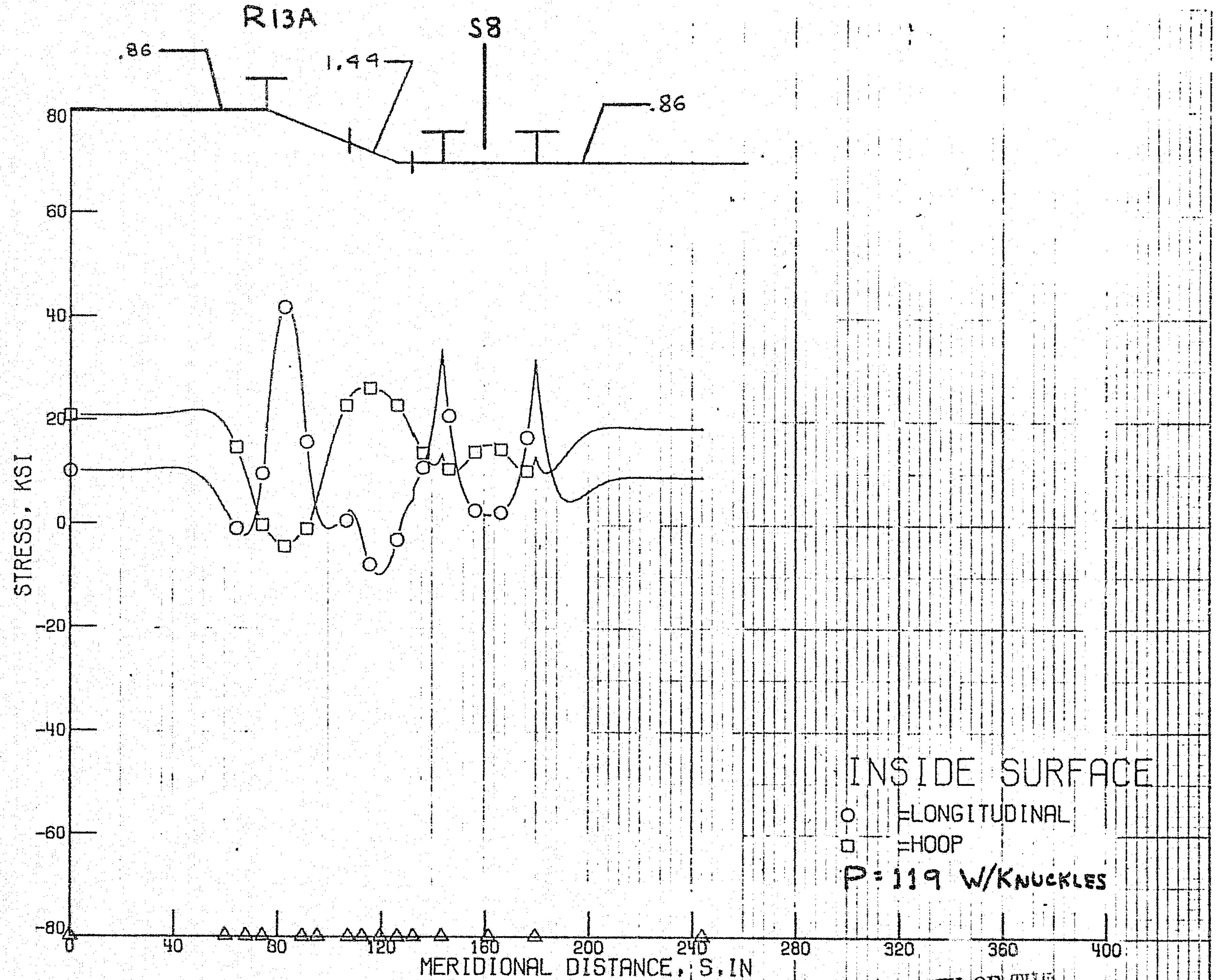

R13A
S8
.86
1.49
.86
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P=119 W/KNUCKLES

Figure 35

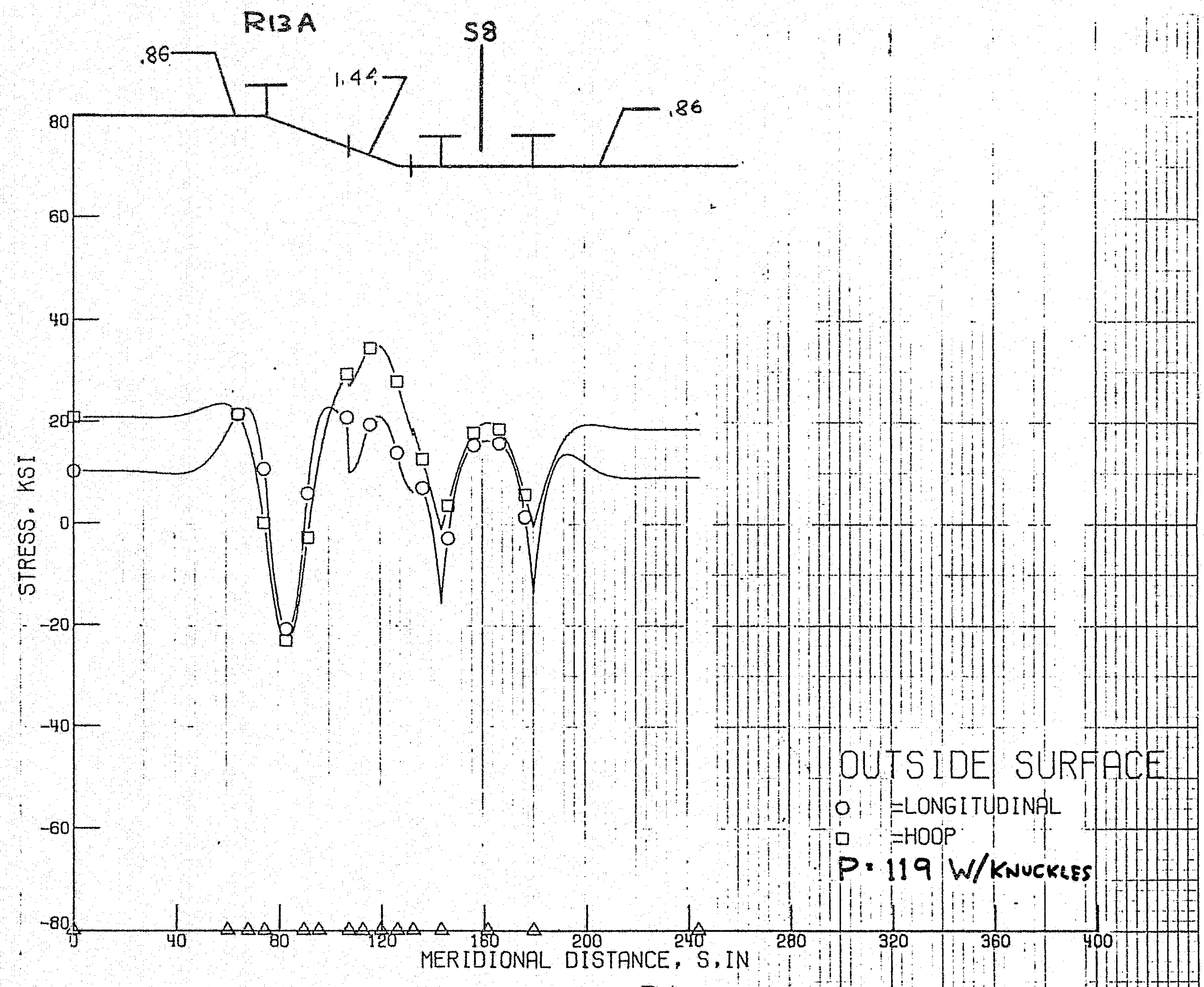
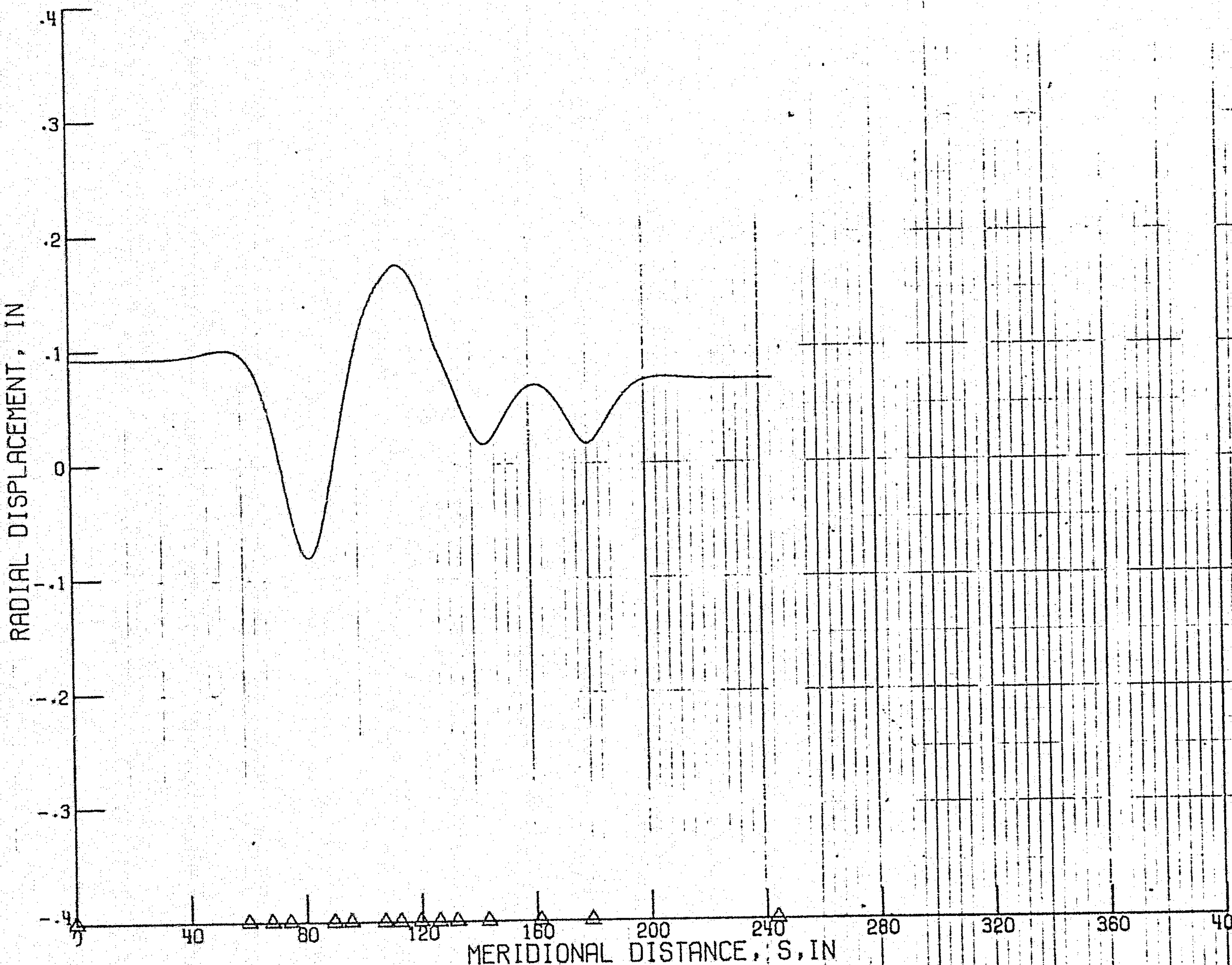

R13A
S8
.86
1.44
.86
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 119 W/KNUCKLES

Figure 36



RADIAL DISPLACEMENT, IN
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S, IN

Figure 37

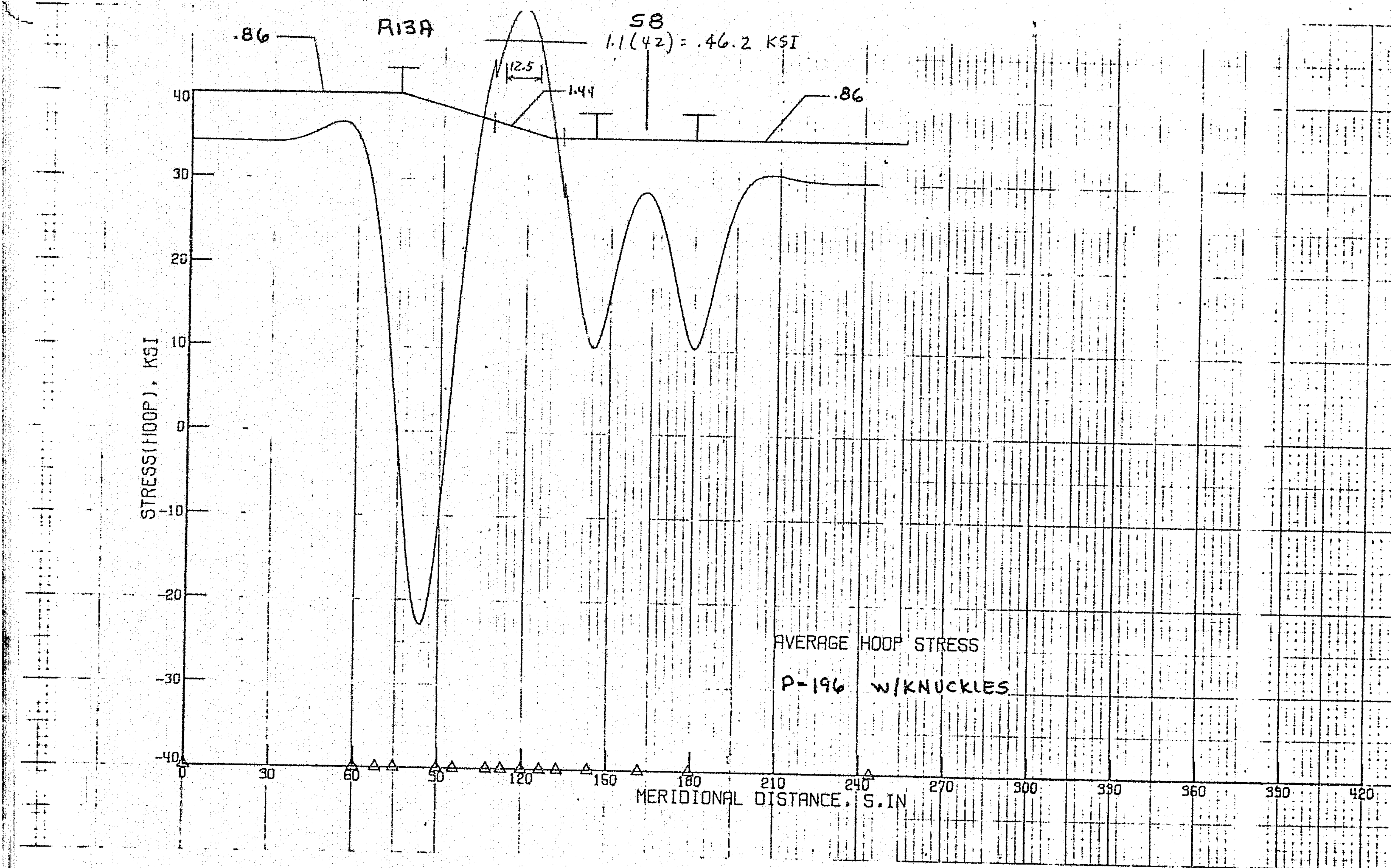
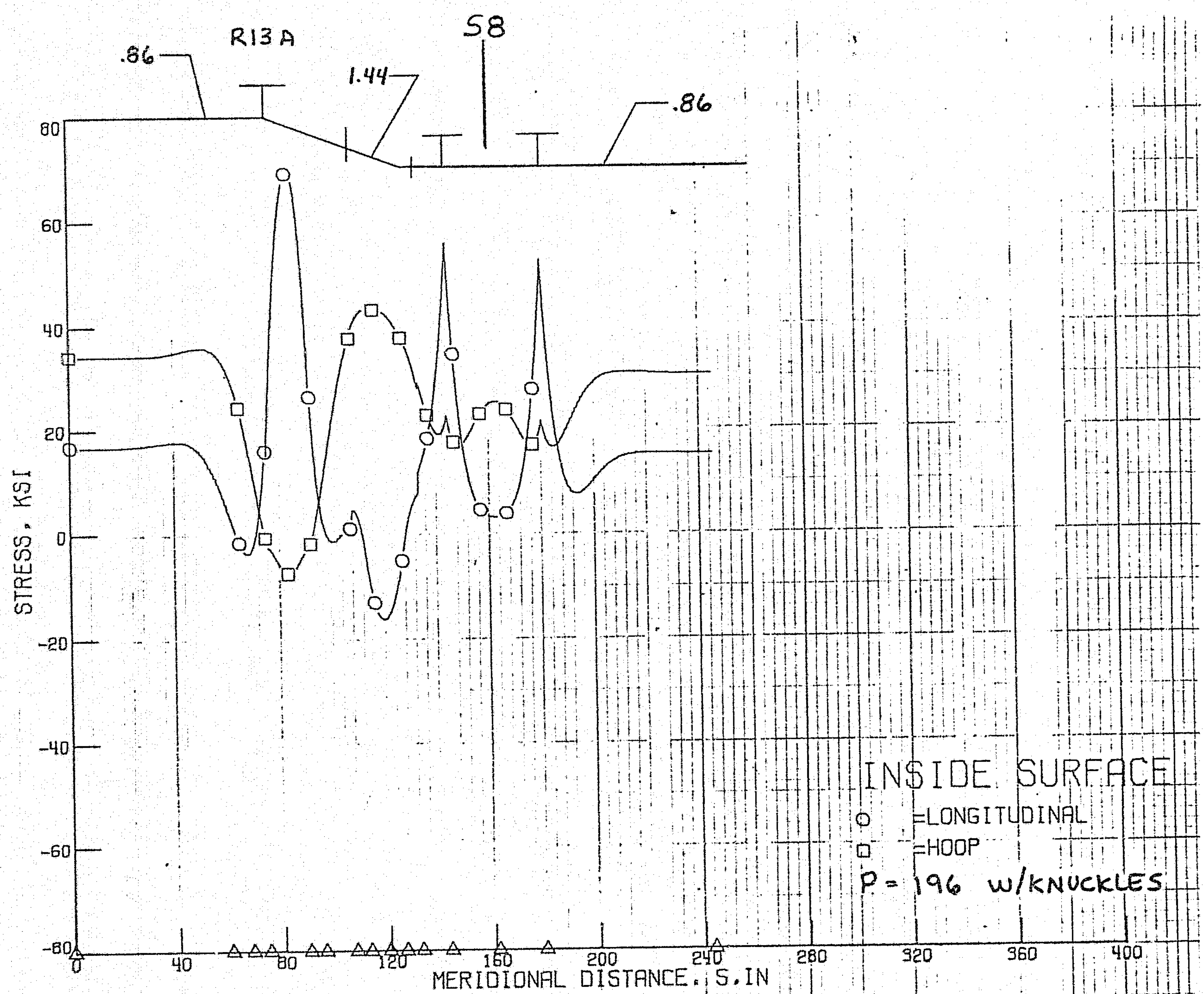

.86
R13A
58
1.1(42) = .46.2 KSI
12.5
1.44
.86
STRESS(HOOP), KSI
40
30
20
10
0
-10
-20
-30
-40
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S.IN
AVERAGE HOOP STRESS
P-196 W/KNUCKLES

Figure 38


R13 A
S8
.86
1.44
.86
STRESS, KSI
80
60
40
20
0
-20
-40
-60
-80
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S, IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 196 w/KNUCKLES

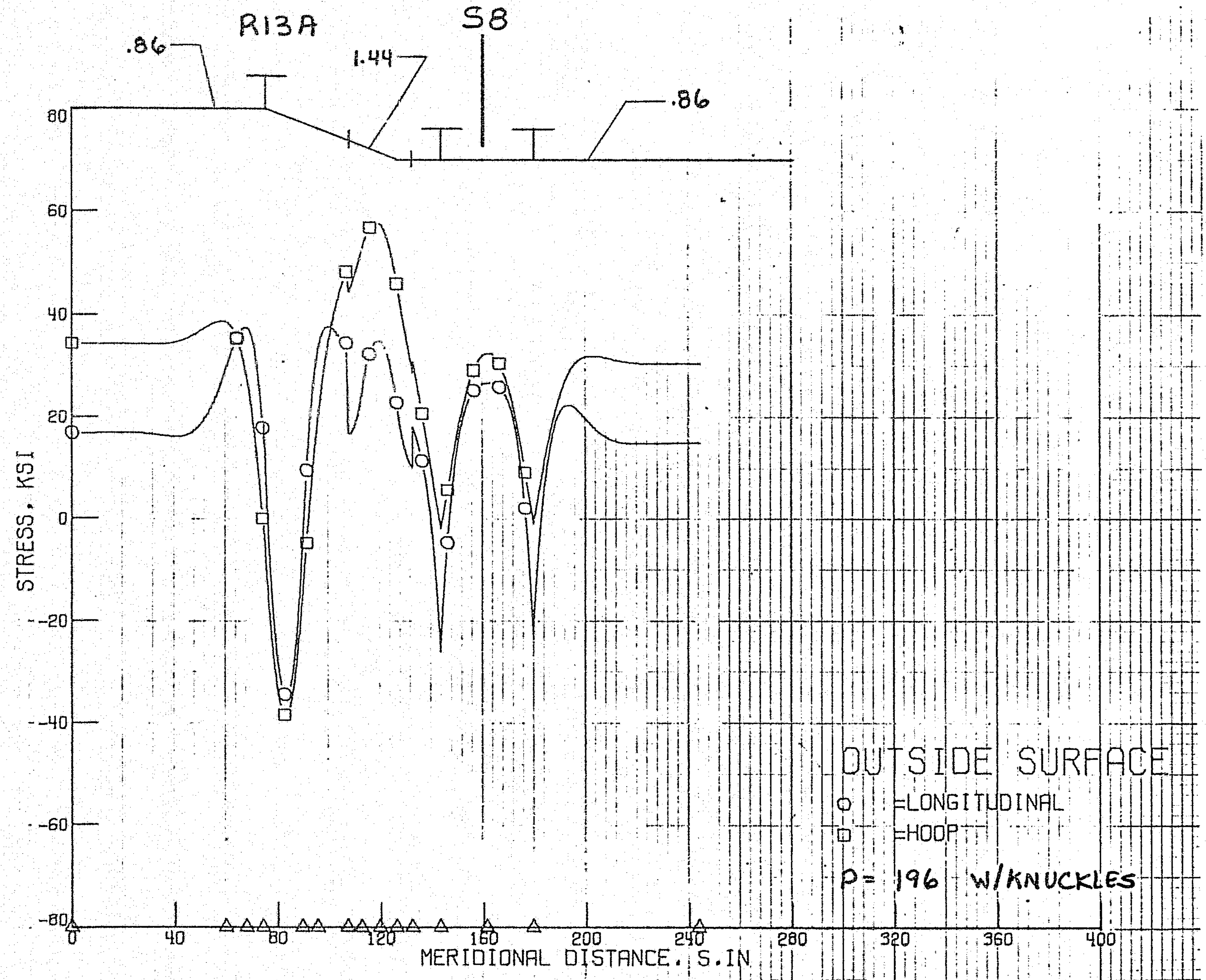

R13A
S8
.86
1.44
.86
STRESS, KSI
80
60
40
20
0
-20
-40
-60
-80
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P= 196 W/KNUCKLES

Figure 40

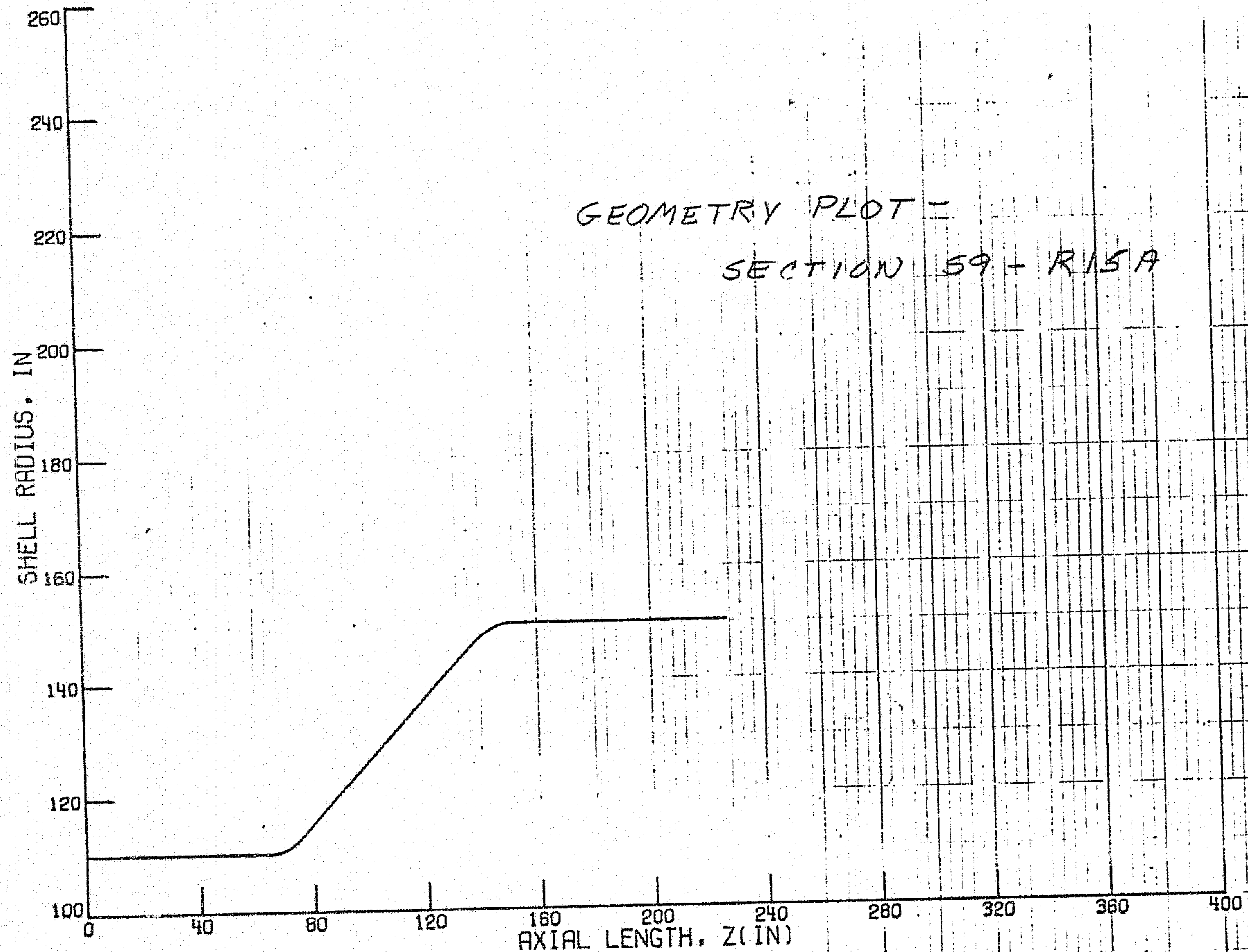

GEOMETRY PLOT –
SECTION 59 - R15A
SHELL RADIUS, IN
260
240
220
200
180
160
140
120
100
0
40
80
120
160
200
240
280
320
360
400
AXIAL LENGTH, Z(IN)

Figure 41

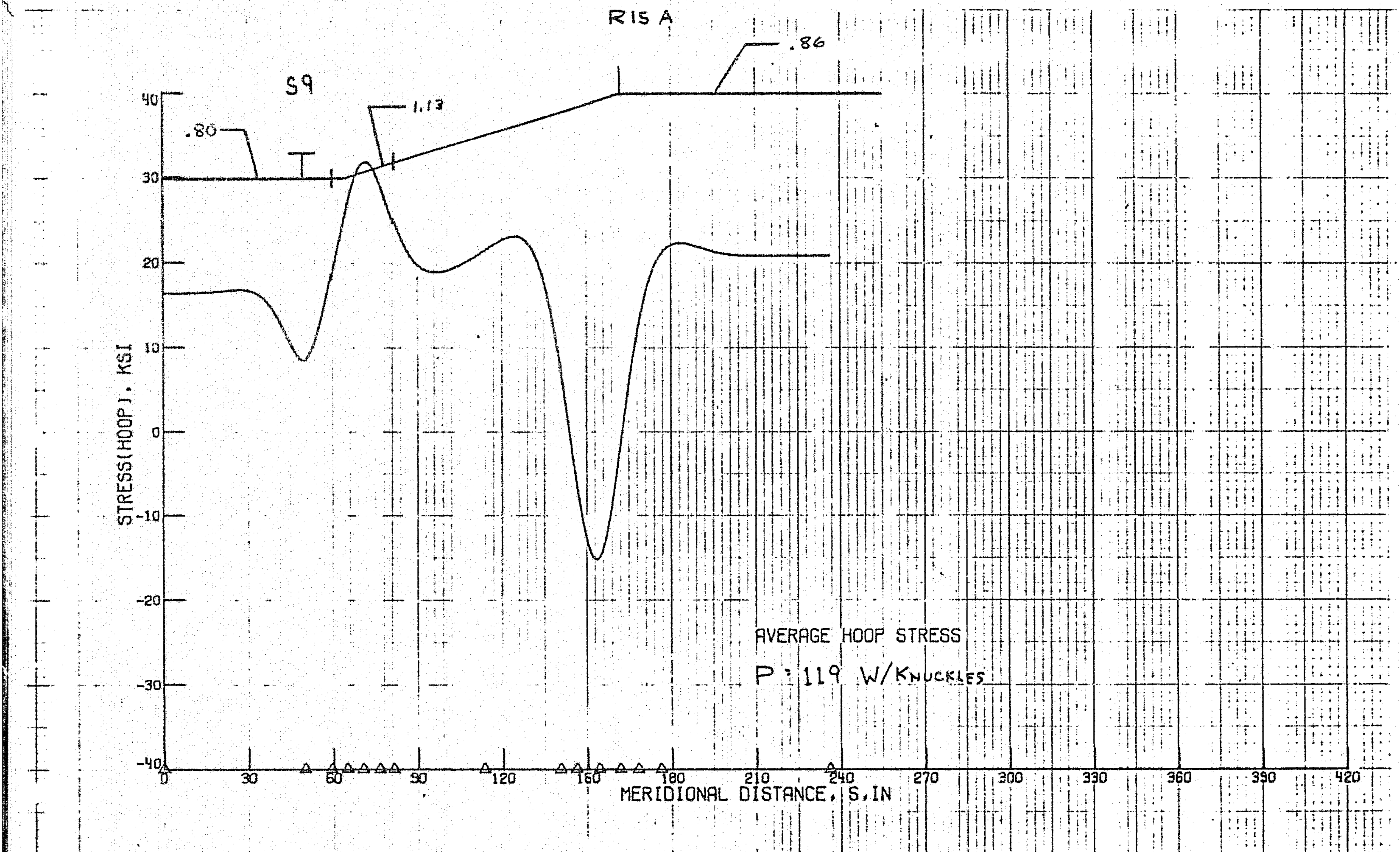

R15 A
S9
.86
1.13
.80
STRESS(HOOP), KSI
40
30
20
10
0
-10
-20
-30
-40
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S,IN
AVERAGE HOOP STRESS
P: 119 W/KNUCKLES

Figure 42

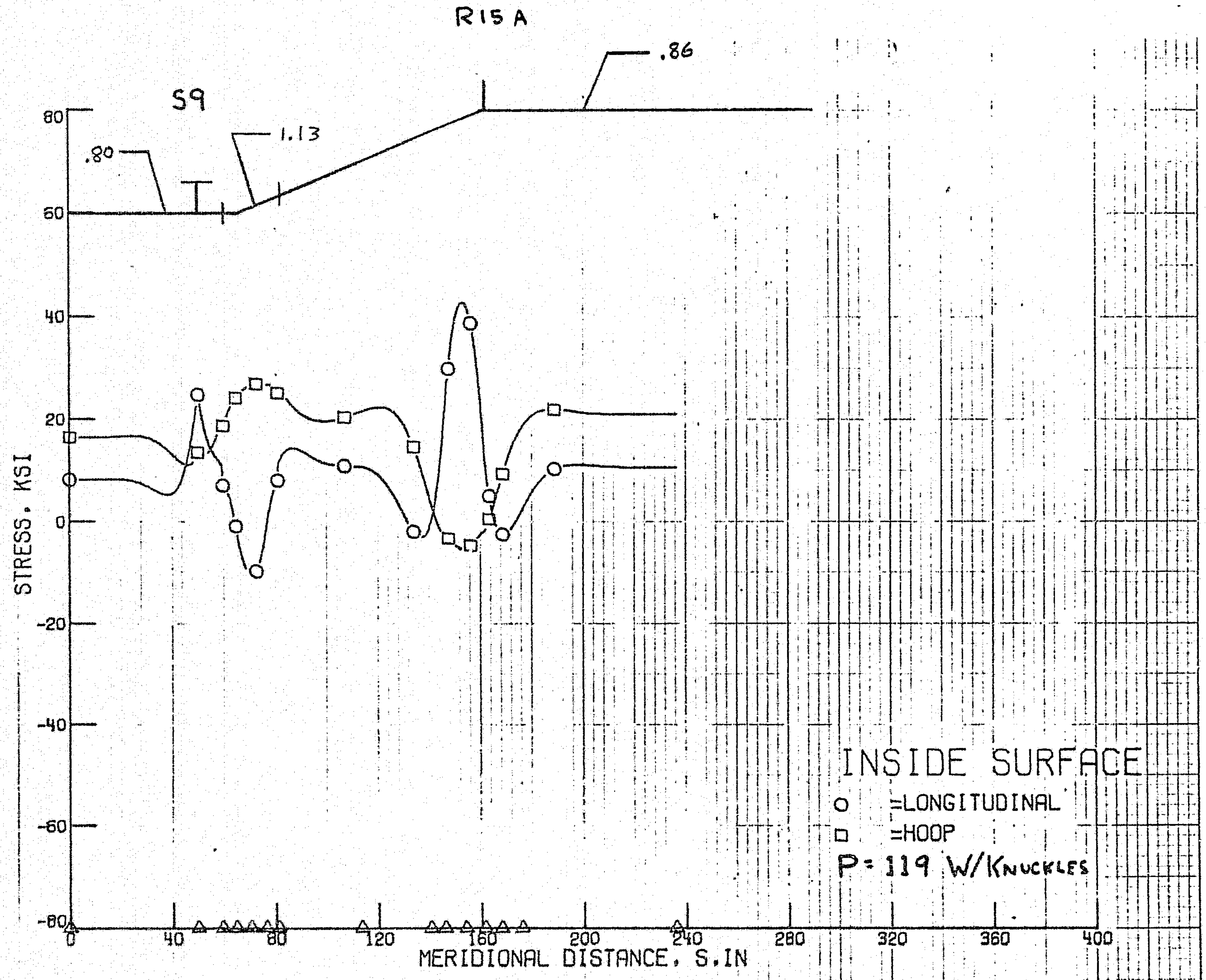
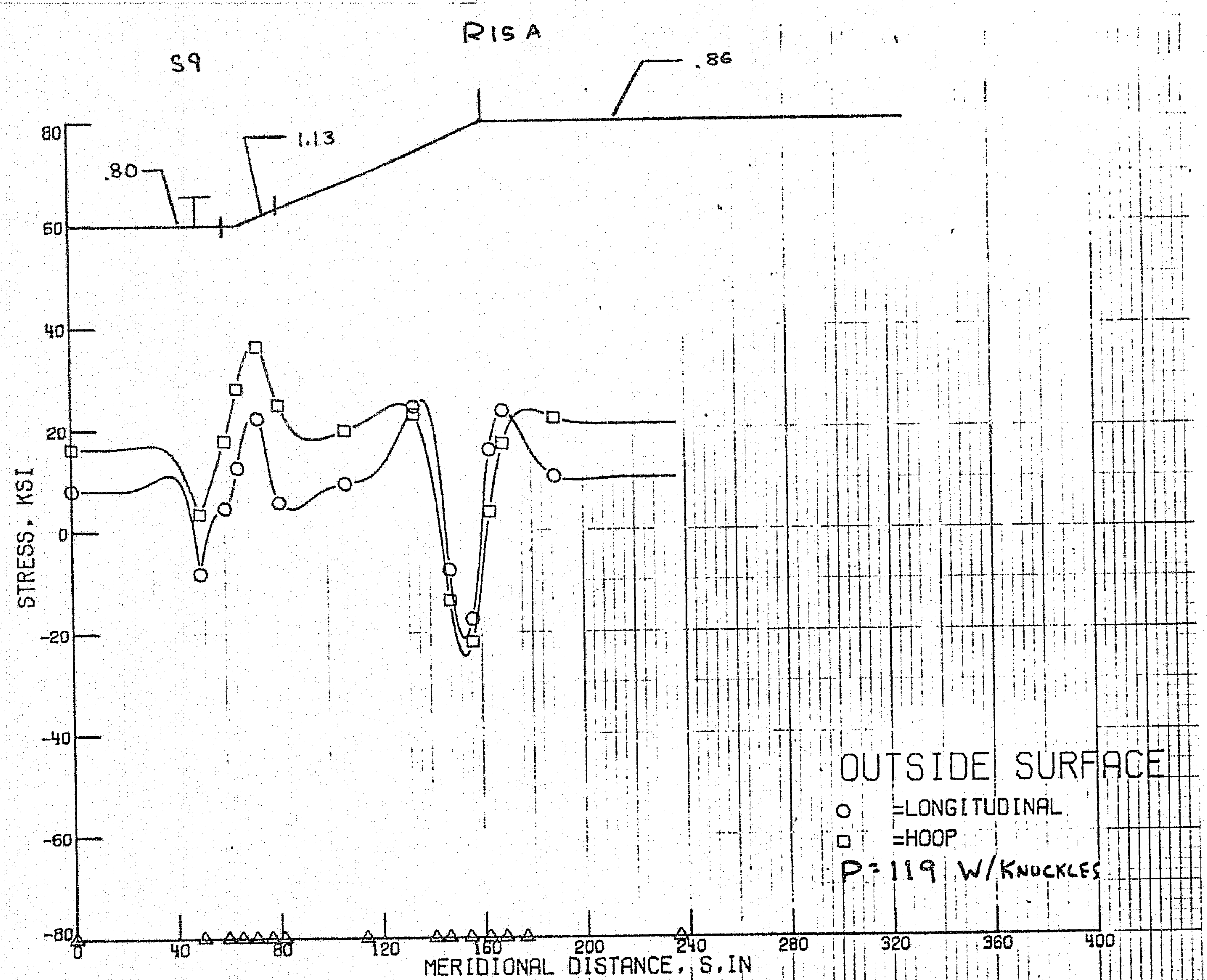
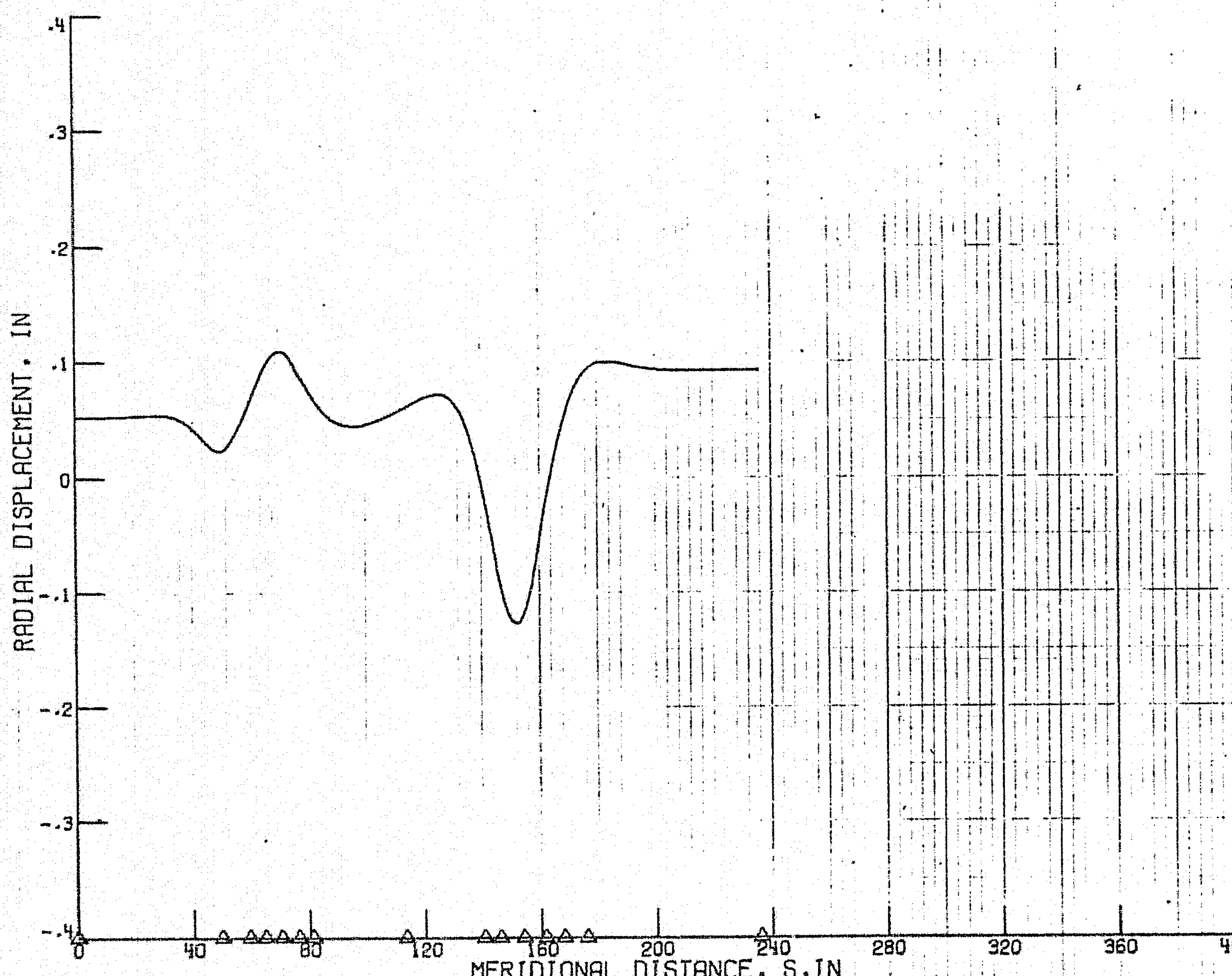

R15A
S9
.80
1.13
.86
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P= 119 W/KNUCKLES

Figure 43



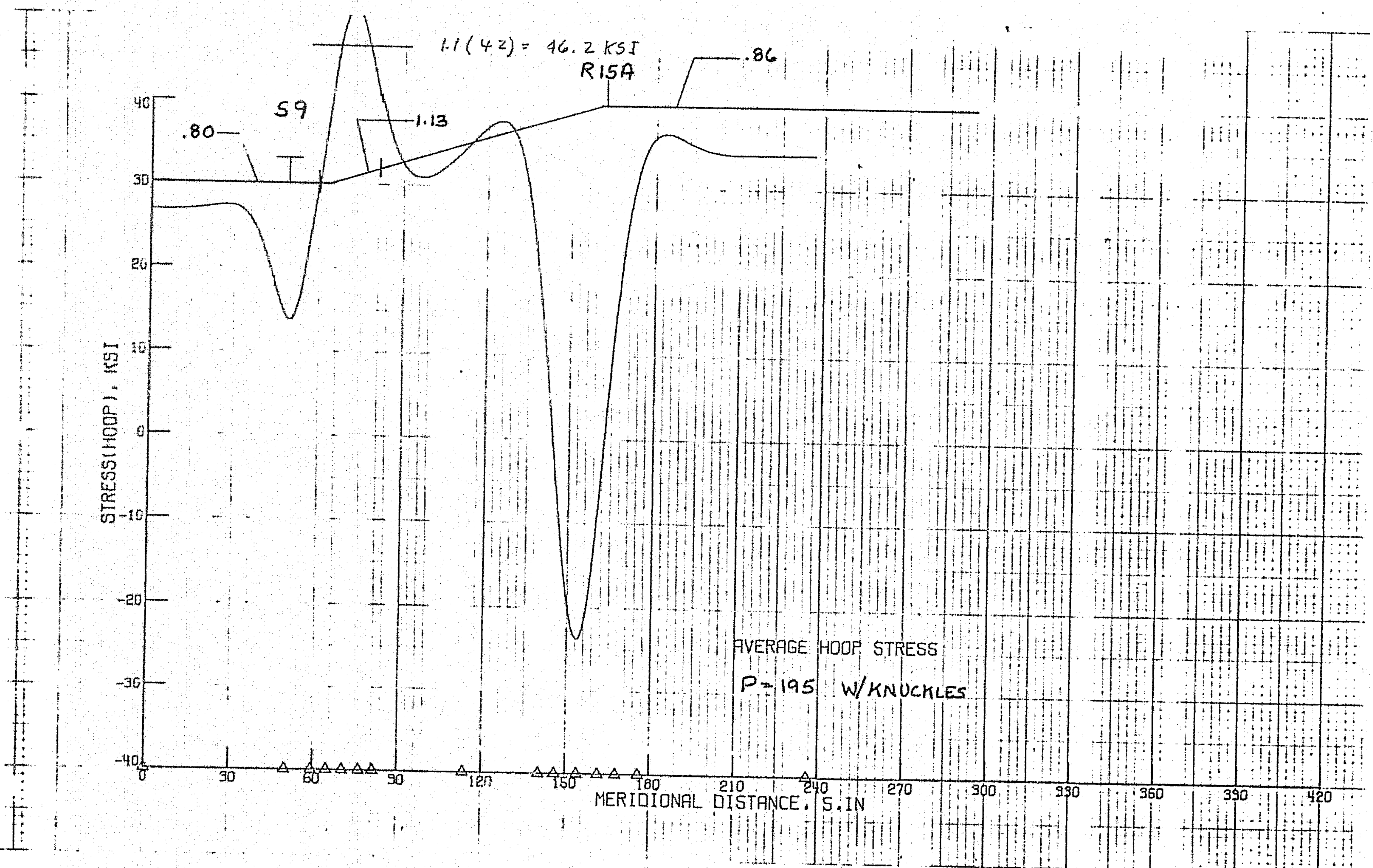
R IS A
S9
.86
1.13
.80
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
=LONGITUDINAL
=HOOP
P=119 W/KNUCKLES

Figure 47



RADIAL DISPLACEMENT, IN
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN

Figure 45



1.1 (42) = 46.2 KSI
R15A
.86
59
.80
1.13
STRESS(HOOP), KSI
40
30
20
10
0
-10
-20
-30
-40
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
MERIDIONAL DISTANCE, S,IN
AVERAGE HOOP STRESS
P=195 W/KNUCKLES

Figure 46

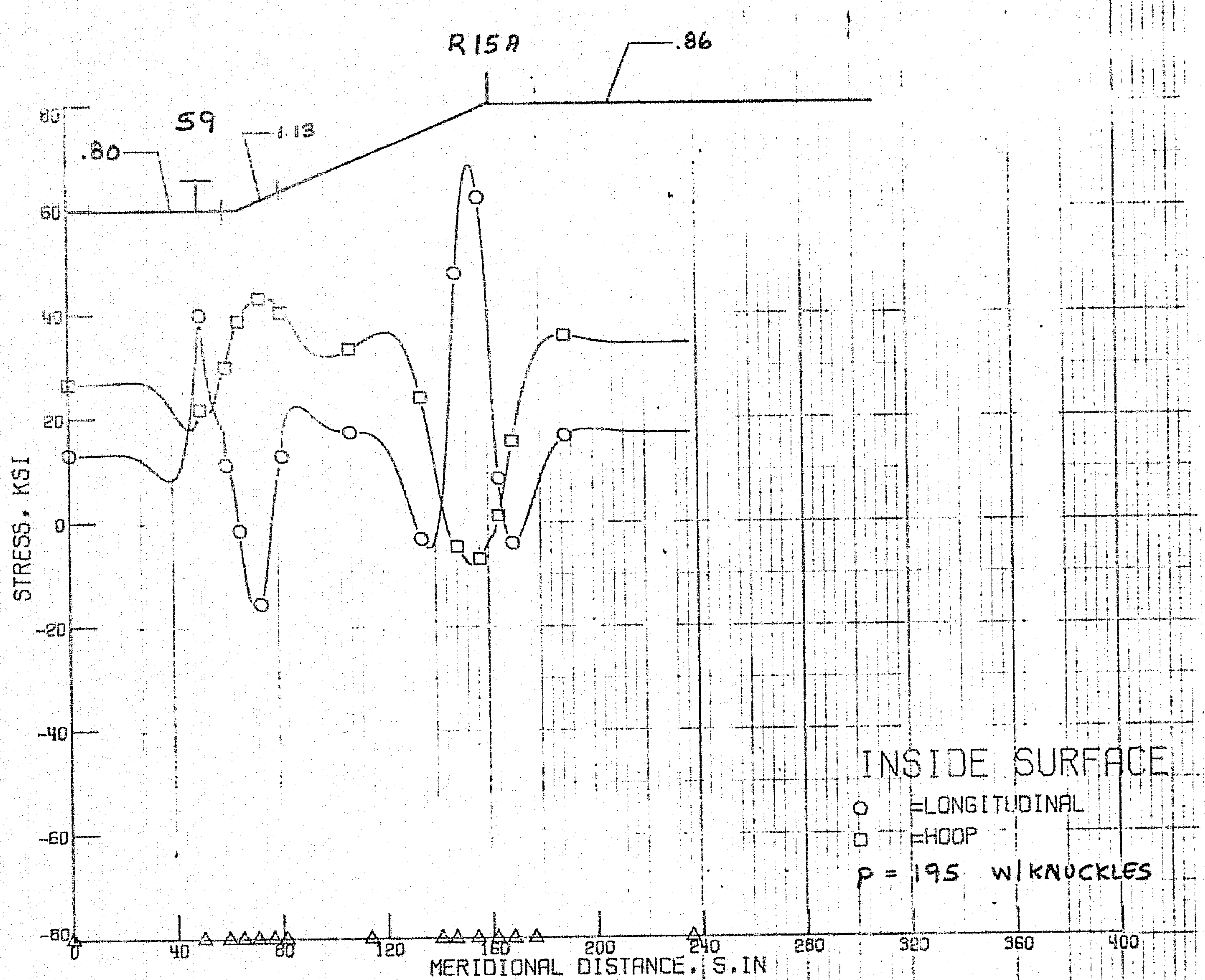

R15A
.86
S9
.80
1.13
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S,IN
INSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 195 W/KNUCKLES

Figure 47

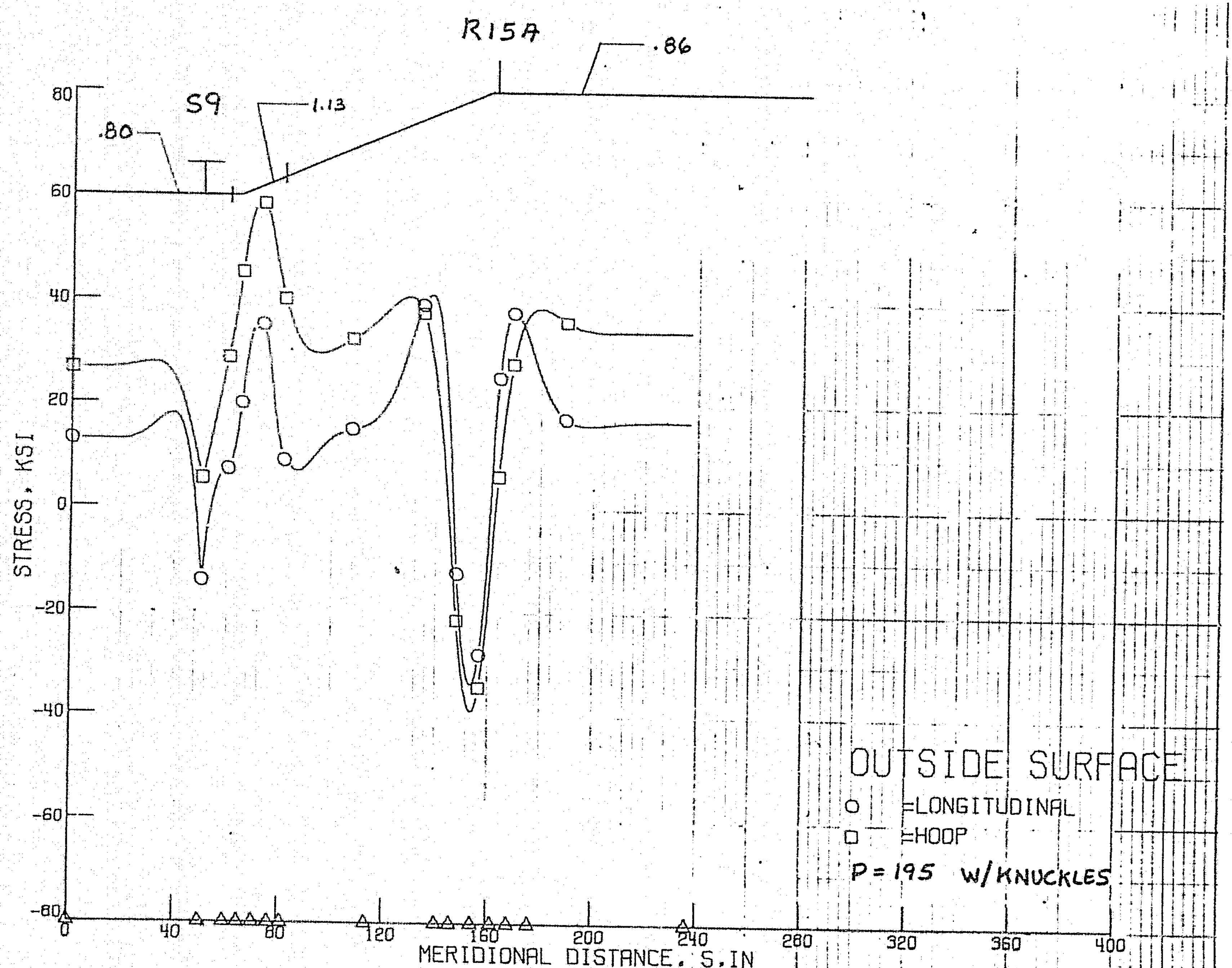

R15A
.86
S9
1.13
.80
80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
40
80
120
160
200
240
280
320
360
400
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
○ =LONGITUDINAL
□ =HOOP
P = 195 W/KNUCKLES

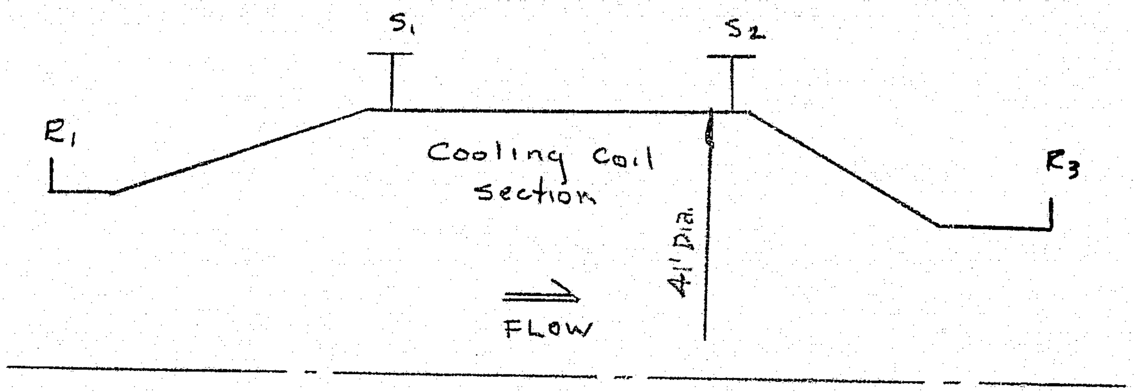
Figure 48

BY .... DATE .... SUBJECT NTF Pressure Shell
CHKD. BY .... DATE .... Stress Variation in Shell due to Hydro Conditions

SHEET NO. 1 OF ....
JOB NO. ....

Part 2

The following section of the tunnel was modeled using Nastran.



Note:

This is <u>not</u> a detailed analysis of this section of the Tunnel.

The following computer results and hand calculations are used only to verify stress scalings due to Hydro Test conditions

BY .... DATE .... SUBJECT .... SHEET NO. 2 OF ....
CHKD. BY .... DATE .... JOB NO. ....

Hastran (Nasa Structural analysis) is a general purpose digital computer program for the analysis of large complex structures.

Nasa SP-222(01)

Nastran model description

This section of the tunnel was modeled using homogenious quadrilaterial membrane and bending elements. except for R_1 & R_3 which were modeled using beam elements.

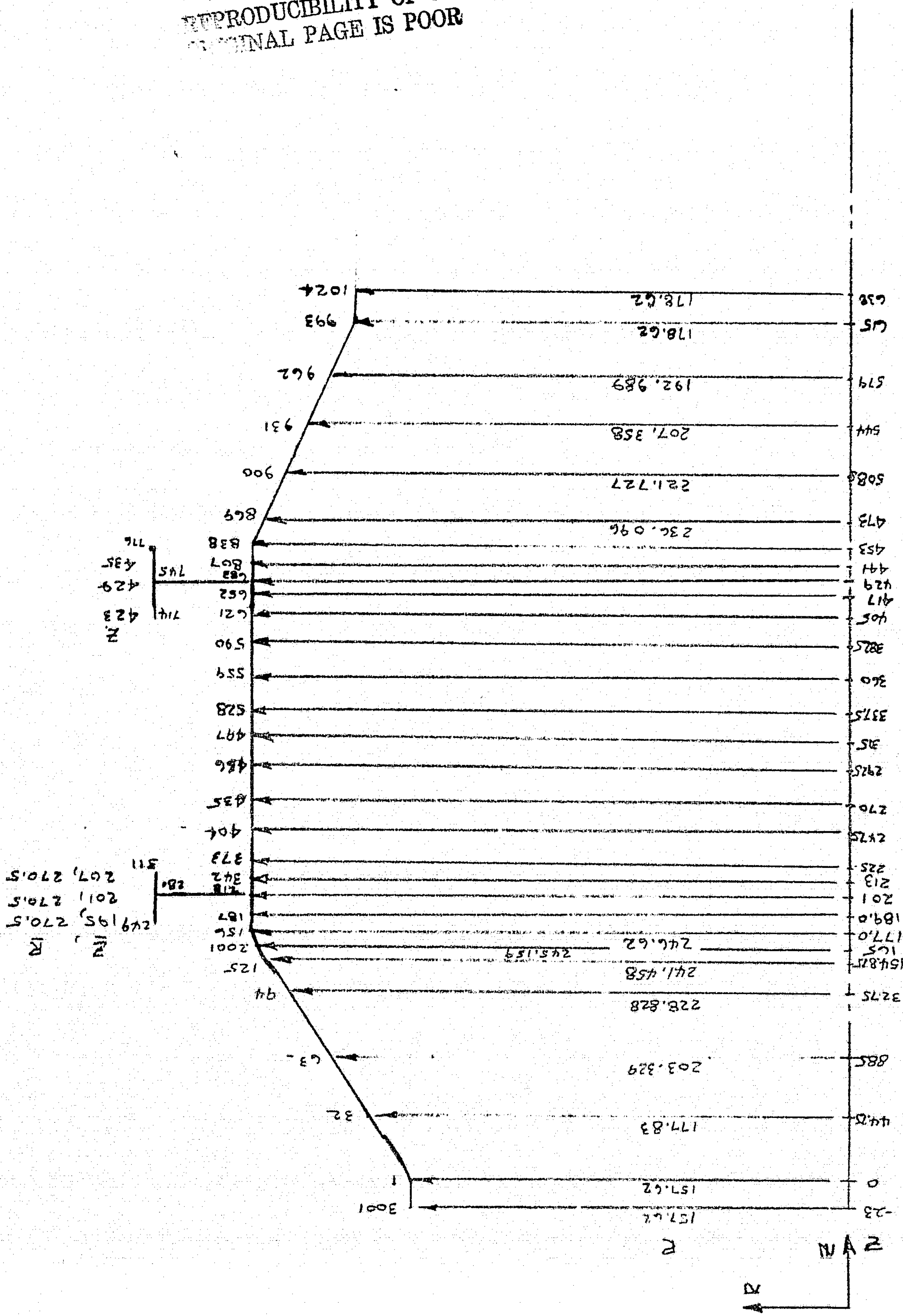
Due to the need of modeling a varable pressure, a half model using 31 elements around the circumference was generated.

See figure 1 for a joint location sketch of this area

BY ______________ DATE ________ SUBJECT ________________________________ SHEET NO. 4 OF ____

CHKD. BY ________ DATE ________ JOB NO. ________________

NASTRAN COARSE MODEL



BY .... DATE	SUBJECT	SHEET NO. 5 OF .....
CHKD. BY .... DATE		JOB NO. ....

Constraints.

The R, Z plane was modeled as a plane of symmetry.

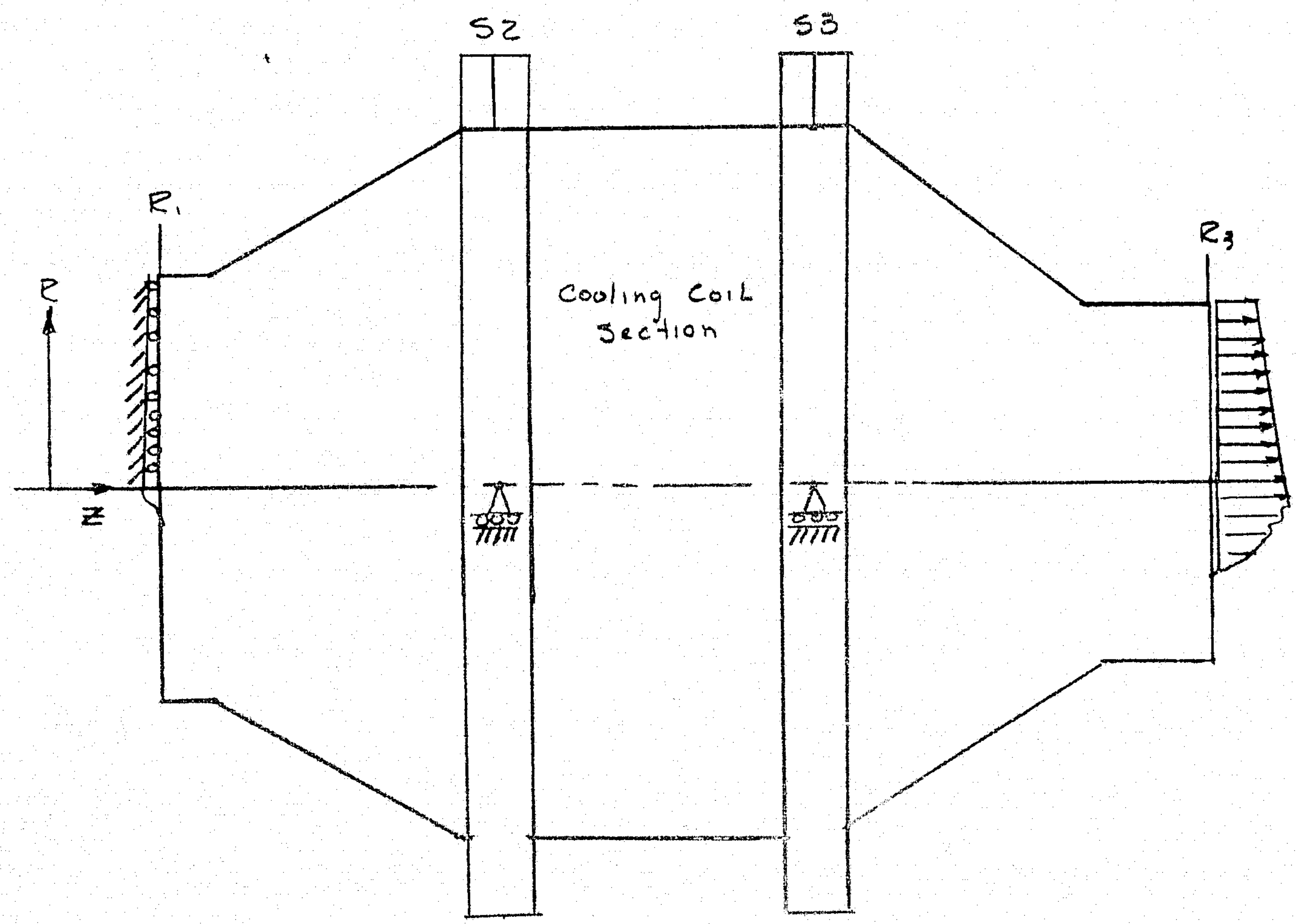
on the R_1 end of the model the Z displacement and rotations were removed.

on the R_3 end of the model all rotions were removed.

The rotation normal to the shell elements was removed

nodes on the flange of the support tee S2 and S3 located at $\theta = 90$ were fixed in the Vertical direction. (fig 2)

Boundary Conditions



Model geometry

as previously mentioned a half model with 31 elements around the circumference and 1117 nodes, was generated.

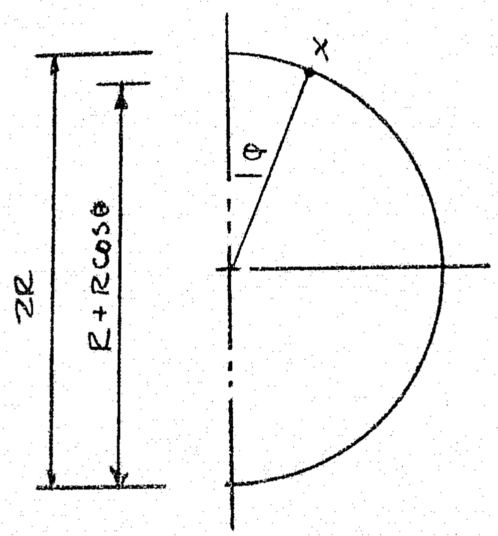
The model ran from ring location R1 To ring location R3.

all shell thickness were 1.24" except for the down stream shell past the second cone cylinder junction. this thickness was 1.00".

Material Constants
$E = 30 \times 10^6$ PSI
$\nu = 0.3$
$\rho = .283$ lbs/IN^3

Loading

a uniform element pressure of 119 psig was applied to all shell elements.
In addition to this uniform pressure, a variable pressure due to the water head was added on.



$\gamma = 62.4 \text{ lbs}/ft^3 = .0361 \frac{lb.}{in^3}$

$P_{l_x} = \gamma[2R - (R + R\cos\theta)]$

$P_{l_x} = \gamma(R - R\cos\theta)$

$P_{TEST} = 1.5 \times P_{opp} = 1.5 \times 119 = 178.5$

The variable pressure at any point X around the circumference was defined by $P_{l_x} = \gamma(R - R\cos\theta) + P_{Test}$

Note: all pressures are in psi.

With 31 element around the circumference
The enclosure angle between elements
$180°/30$ spaces $= 6°$

Theta to the first element is $3°$.

Pressure at $\theta = 3°$

$$P_a = 119 \times 1.5 + .0361(20.5 \times 12 - 20.5 \times 12 \times \cos(3))$$
$$= 178.55 \text{ PSI}$$

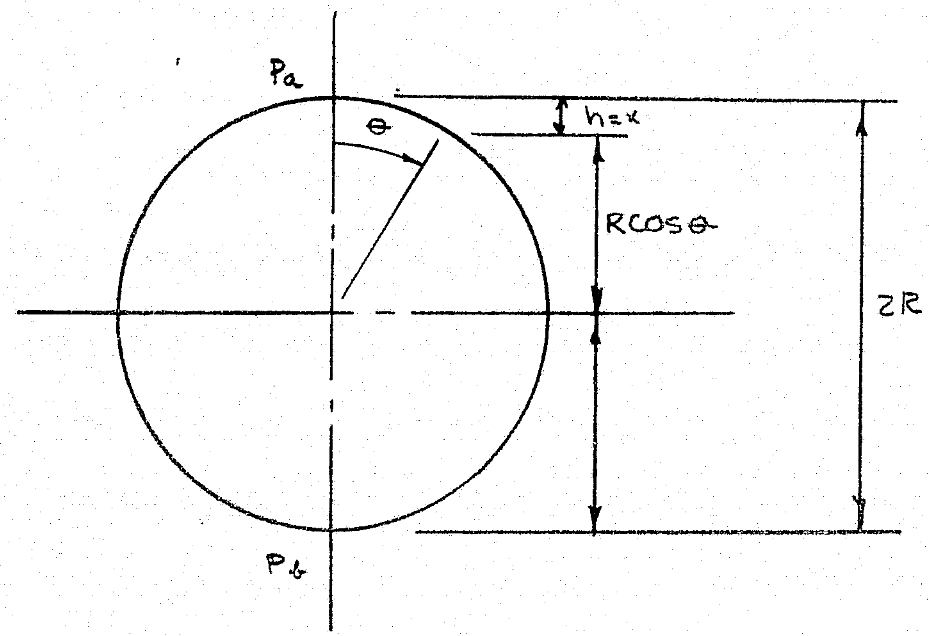
Pressure at $\theta = 180°$

$$P_b = 119 \times 1.5 + .0361(20.5 \times 12 - 20.5 \times 12 \times \cos(180))$$
$$P_b = 196.23 \text{ psi}$$

Where $(119 \times 1.5) = 178.5$ psi is the Hydro test pressure.

$\gamma R(1 - \cos\theta)$ is the additional pressure at any point due to the water head.

a linear Variable end force was applied To the R_3 end of the model given by



$h = 2R - [R + R\cos\theta]$

$2R - R - R\cos\theta$

$R[2 - 1 - \cos\theta]$

$R[1 - \cos\theta]$

$P = \left(\frac{P_b - P_a}{2R}\right)x + P_a$

$P = \frac{\Delta P}{2R}\left[R(1 - \cos\theta)\right] + P_a$

$$\text{Pressure}\Big|_x = \frac{\Delta P}{2}\left[1 - \cos\theta\right] + P_a \,.$$

BY ____ DATE ____ SUBJECT ____ SHEET NO. 11 OF ____
CHKD. BY ____ DATE ____ JOB NO. ____

Results

The primary purpose for this model was to verify that scaling of opperating stresses to hydo stresses wouldn't generate any incorrect stresses results.

also, note that this section of The tunnel has the highest and lowest elevation. There fore, The highest pressure dece to the water head.

Water weights - from computer run GT 78007

Node	Constraint Reaction lbs
264	-5.59934×10^4
295	-4.44728×10^5
362	-5.115345×10^4
729	-5.441023×10^4
760	-4.59041×10^5
791	-5.556915×10^4
3016	-4.098632×10^5
1039	-3.277161×10^5
TOTAL	1858475. lbs

Calculated

Weight of water in this section of the tunnel. 1851719.0 lbs.

Calculated	1851719.0	lbs
Model generated	1858475.0	lbs
Δ Water weight	-6756.0	lbs.
	.36 %	diff.

BY	DATE	SUBJECT	SHEET NO. 13 OF
CHKD. BY	DATE		JOB NO.

opperating pressure $P = 119.00$

(Top) Hydro pressure at element 2001 = .0483 + 178.5 = 178.55 psi

(bottom) Hydro pressure at element 2030 = 17.73 + 178.5 = 196.23 psi

Scale factor for top of tunnel:

$$\frac{178.55}{119} = 1.5004$$

Scale factor for bottom of tunnel:

$$\frac{196.23}{119} = 1.649$$

From Nastran run GT 78007 w/ P=119
(Peak stresses)

element	σ_{Hoop} KSI inside	σ_{Hoop} KSI outside	σ_{axial} KSI inside	σ_{axial} KSI outside	Location
2001	-4.43	-13.9	+27.59	-3.71	$\theta = 0°$
2030	-4.44	-13.9	+27.59	-3.71	$\theta = 180°$

Scaled stresses from above

element	σ_{Hoop} inside	σ_{Hoop} outside	σ_{axial} inside	σ_{axial} outside	Scale factor
2001	-6.647	-20.86	+41.396	-5.57	1.5
2030	-7.32	-22.92	+45.50	-6.12	1.649

Stresses from Hydro run $P = 178.5 + H_2O$ head

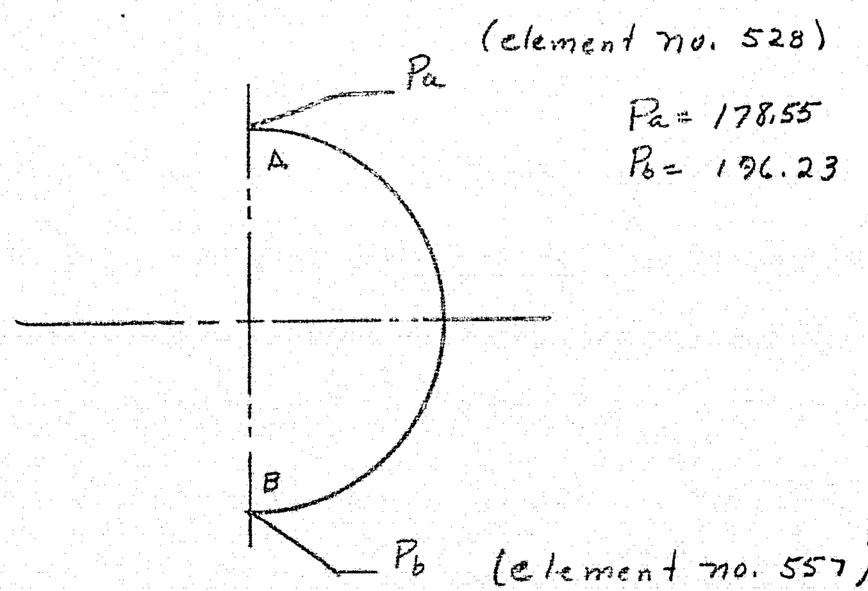
element	σ_{Hoop} KSI inside	σ_{Hoop} KSI outside	σ_{axial} KSI inside	σ_{axial} KSI outside	Location
2001	-7.14	-21.6	42.0	-5.71	$\theta = 0°$
2030	-7.15	-22.6	45.23	-6.03	$\theta = 180°$

BY ______ DATE ______ SUBJECT ______ SHEET NO. 14 OF ______

CHKD. BY ______ DATE ______ JOB NO. ______

as can be seen from the last two tables, scaling of opperating stresses does not generate any erroneous stresses.

To add additional verification to the above procedure. Some hand Calculations To predict stresses in the region between support ring were made.



For Hydo Conditions.

At point A. element No. 528

$R = 246.62$ $\theta = 0°$ $P_a = 178.55$ PSI

$\sigma_{Hoop} = (178.55 \times 246.62) / 1.24 = 35511$ PSI

at point B element no. 557

$R = 246.62$ $\theta = 180°$ $P_b = 196.23$

$\sigma_{Hoop} = (196.23 \times 246.62) / 1.24 = 39027.$ PSI

From Nastran run no. GT 78007 :

at element no. 528

σ_{Hoop} (inside) = 35508.9

σ_{Hoop} (OUTSIDE) = 35405.8

$\sigma_{ave} = 35457$ PSI

at element no. 557

σ_{Hoop} (inside) = 38929

σ_{Hoop} (outside) = 39025

$\sigma_{ave} = 38977$ PSI

element	Hand Calculation	Computer results	θ	
528	35.5 KSI	35.5 KSI	0°	
557	39.0 KSI	39.0 KSI	180°	

In conclusion the following method was used in predicting hydro test stresses from opperating conditions.

Upper center line

$$P_{hydro} = 119 \times 1.5 + \gamma(41 \times 12/2 + D_L \times 12/2)$$

$\gamma = 0.0361$ lbs/in^3

D_L = LOCAL DIAMETER.

Lower Center line

$$P_{hydro} = 119 \times 1.5 + \gamma(41 \times 12/2 + D_L \times 12/2 + 91.25)$$

There fore,

$$\sigma\text{'s}_{(HYDRO)} = \left\{\sigma\text{'s}_{(opperating)}\right\}\left\{\frac{P_{hydro}}{119.0}\right\}$$

BY ______ DATE ______ SUBJECT NTF PRESSURE SHELL SHEET NO. 1 OF ______
CHKD. BY ______ DATE ______ Effects of Insulation Rings on shell stresses JOB NO. ______

Part 3

Assume a cylinder with no structural support ring and design in accordance with Div I of Code

$$t = \frac{PR}{SE - 0.6P}$$

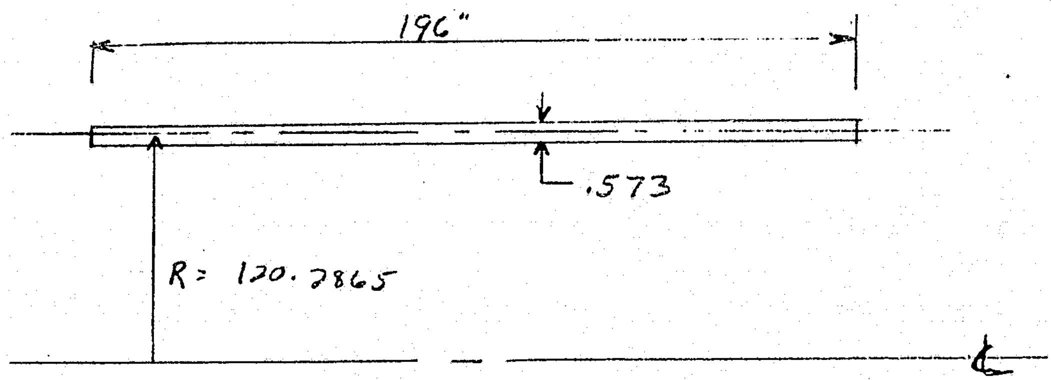
$P = 119$ psig
$R = 120''$
$S = 25.0$ ksi
$E = 1$

$$t = \frac{(119)(120)}{(25000)(1) - 0.6(119)}$$

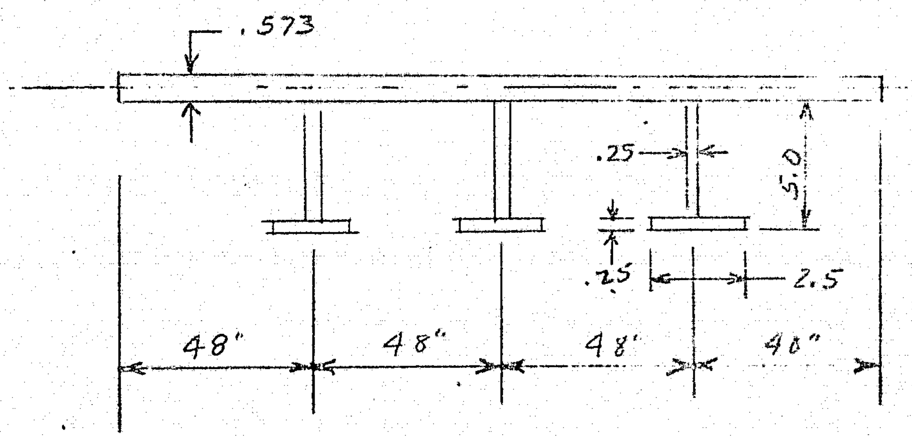
$t = .573$ in.

$$\sigma = \frac{Pr}{t} = \frac{(119)(120.286)}{.573} = 24,980 \text{ psi}$$

Cylinder with insulation rings MODEL 1

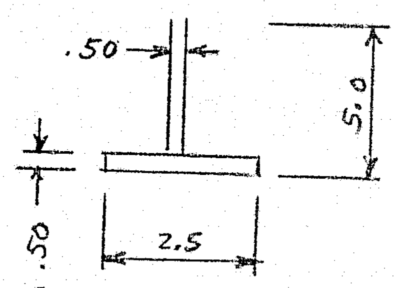


Cylinder with insulation rings Model 2



Cylinder with insulation rings Model 3

Same as model 2 except ring as follows



Boundary Forces

$$F = \frac{(119)(120.2865)}{2}$$

$$F = 7157.05 \text{ lb/in}$$

BY ______ DATE ______ SUBJECT NTF Pressure Shell SHEET NO. 4 OF ____

CHKD. BY ______ DATE ______ Ins. Rings JOB NO. ______

T-SECTION
PROPERTIES.
================

B=	2.500*
D=	5.000*
S=	0.250*
[illegible]	0.250*
H=	4.875
AREA=	1.844
[illegible]	3.267
[illegible]	4.797
[illegible]	0.332

T-SECTION
PROPERTIES.
================

B=	[illegible]
D=	[illegible]
S=	[illegible]
[illegible]	[illegible]
H=	[illegible]
AREA=	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
	[illegible]

Results: (From SALORS)

Cylinder with Insulation Rings # STUDY #

CASE 1 NO RINGS

(76/03/01. 14.00.05)

Hoop Stress = 25,003 psi

Long. Stress = 12,490 psi

rad disp. = .0882 IN.

Case 2. With Insulation Rings t = .25

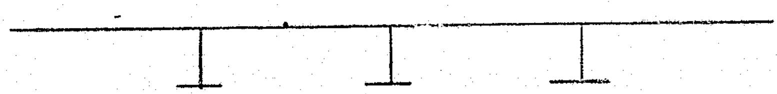
(76/03/01. 14.21.26)

S/SMAX 0 .245 .490 .735 1.00

S/Smax		Long. Stress (PSI)	Hoop Stress (PSI)	Rad. Defl. (IN)	Net Section Hoop
.490	INSIDE	20,329.8	23,605.8	.0701	20647
	outside	4,601.9	18,207.5		
.611	I	12,360.6	25,261.1	.0894	25295
	O	12,588.1	25,329.3		

Case 3 With Insulation Rings $t = 0.50$

76/03/01 14.13.51



s/smax .245 .490 .753 1.00

s/smax		Long Stress (psi)	Hoop Stress (psi)	Rad. defl. (IN)	Net Section Hoop
.366	INSIDE	12277	25426		25482
	OUTSIDE	12650	25538		
.490	INSIDE	25,353	21725		17 224
	OUTSIDE	−4535	13983		
.611	INSIDE	12 277	25426		25482
		12 650	25538		

BY ______ DATE ______ SUBJECT NTF PRESSURE SHELL SHEET NO. 7 OF ______
CHKD. BY ______ DATE ______ Effects of Insulation Rings JOB NO. ______
on Shell Stresses

For 0.25 in thick Rings

$$\frac{25295 - 25003}{25295} = .011$$

∴ Insulation rings results in 1.1% net section stress in Hoop direction

---

For 0.50 in thick Rings

$$\frac{25482 - 25003}{25003} = 0.019$$

∴ Insulat. results in 1.9% net section stress in Hoop direction

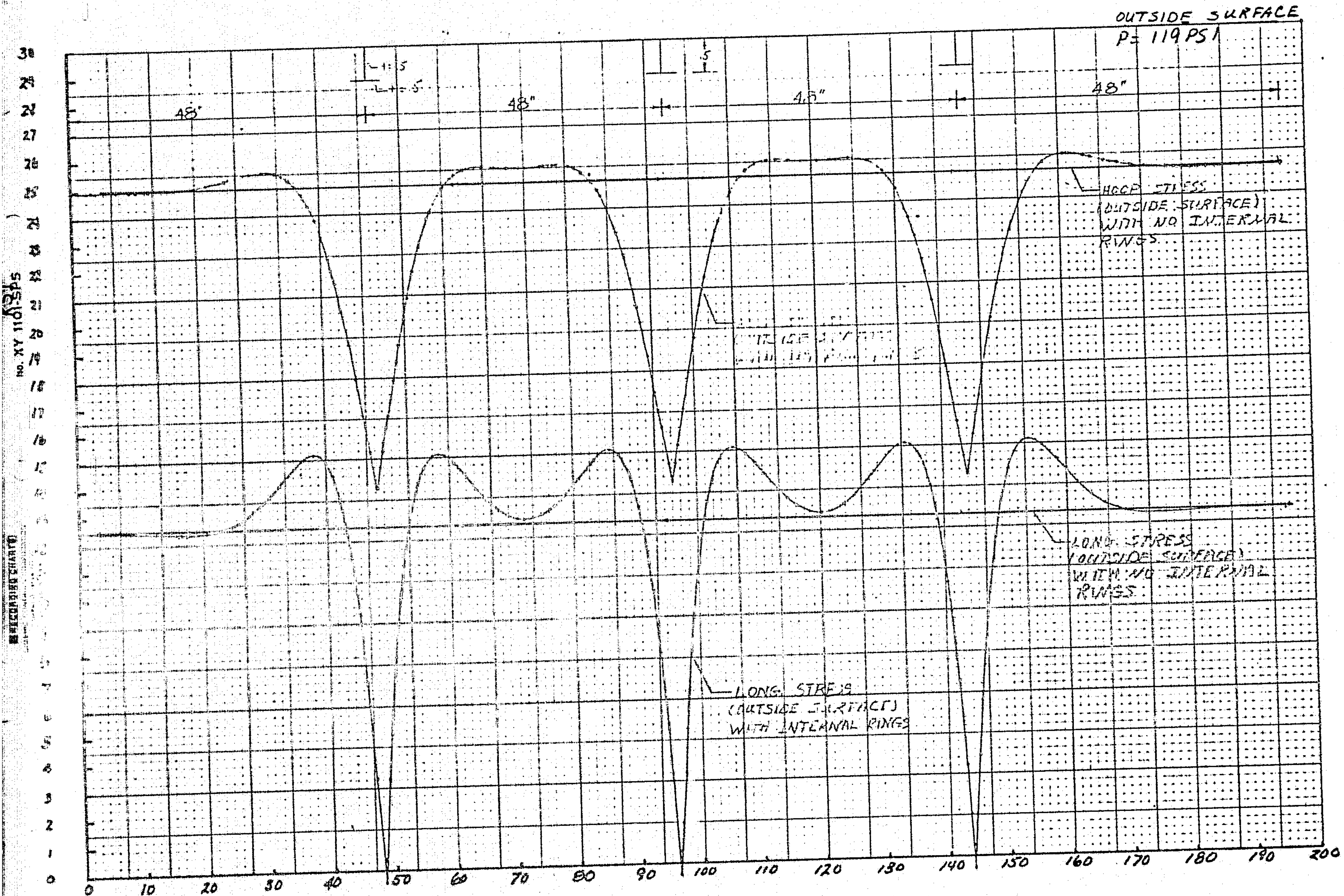


Fig. 1

ODUCIBILITY OF THE
NAL PAGE IS POOR

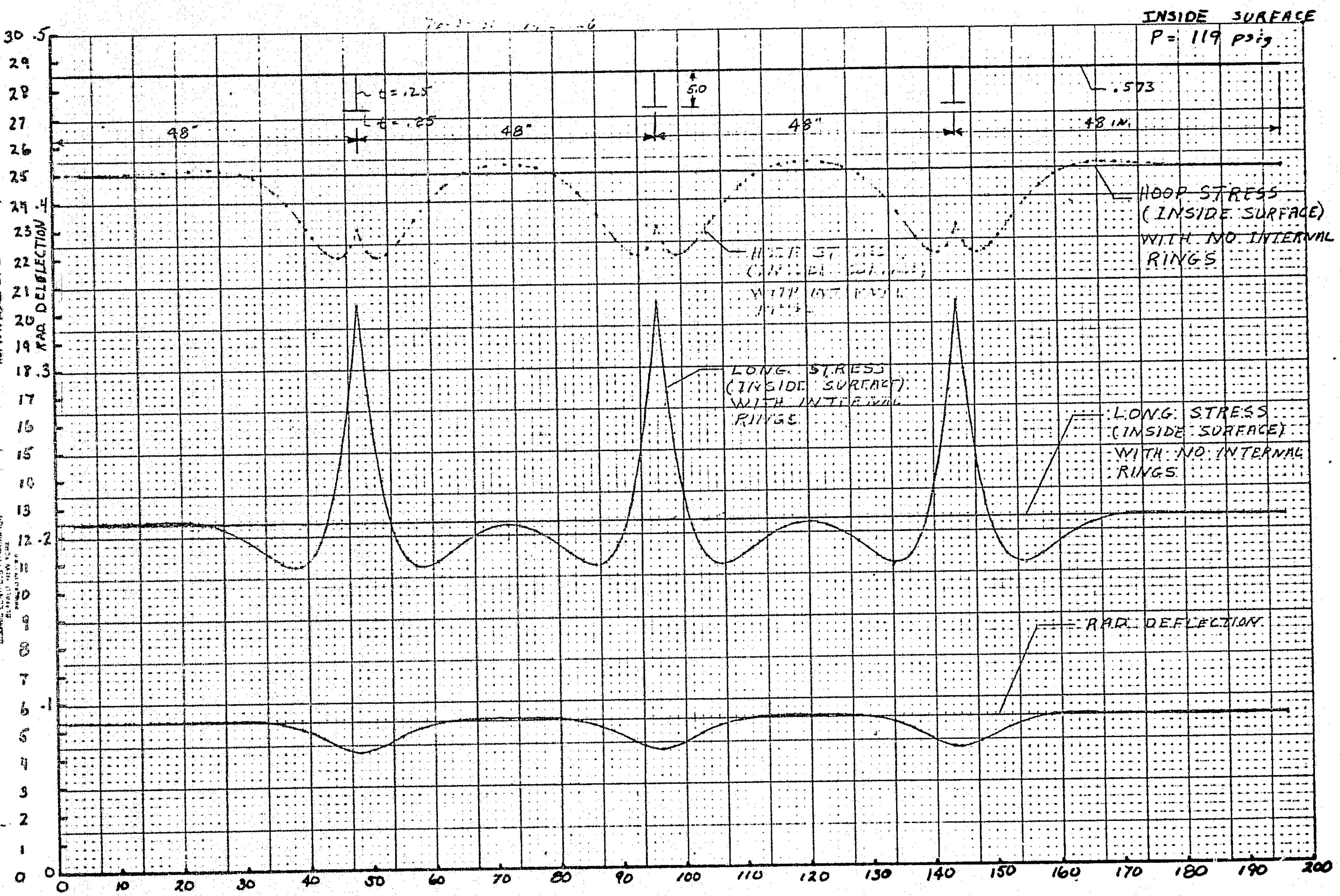

INSIDE SURFACE
P = 119 psig
.573
t = .25
t = .25
5.0
48"
48"
48"
48 IN.
HOOP STRESS (INSIDE SURFACE) WITH NO INTERNAL RINGS
LONG. STRESS (INSIDE SURFACE) WITH INTERNAL RINGS
LONG. STRESS (INSIDE SURFACE) WITH NO INTERNAL RINGS
RAD. DEFLECTION
RAD DEFLECTION
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Fig 2

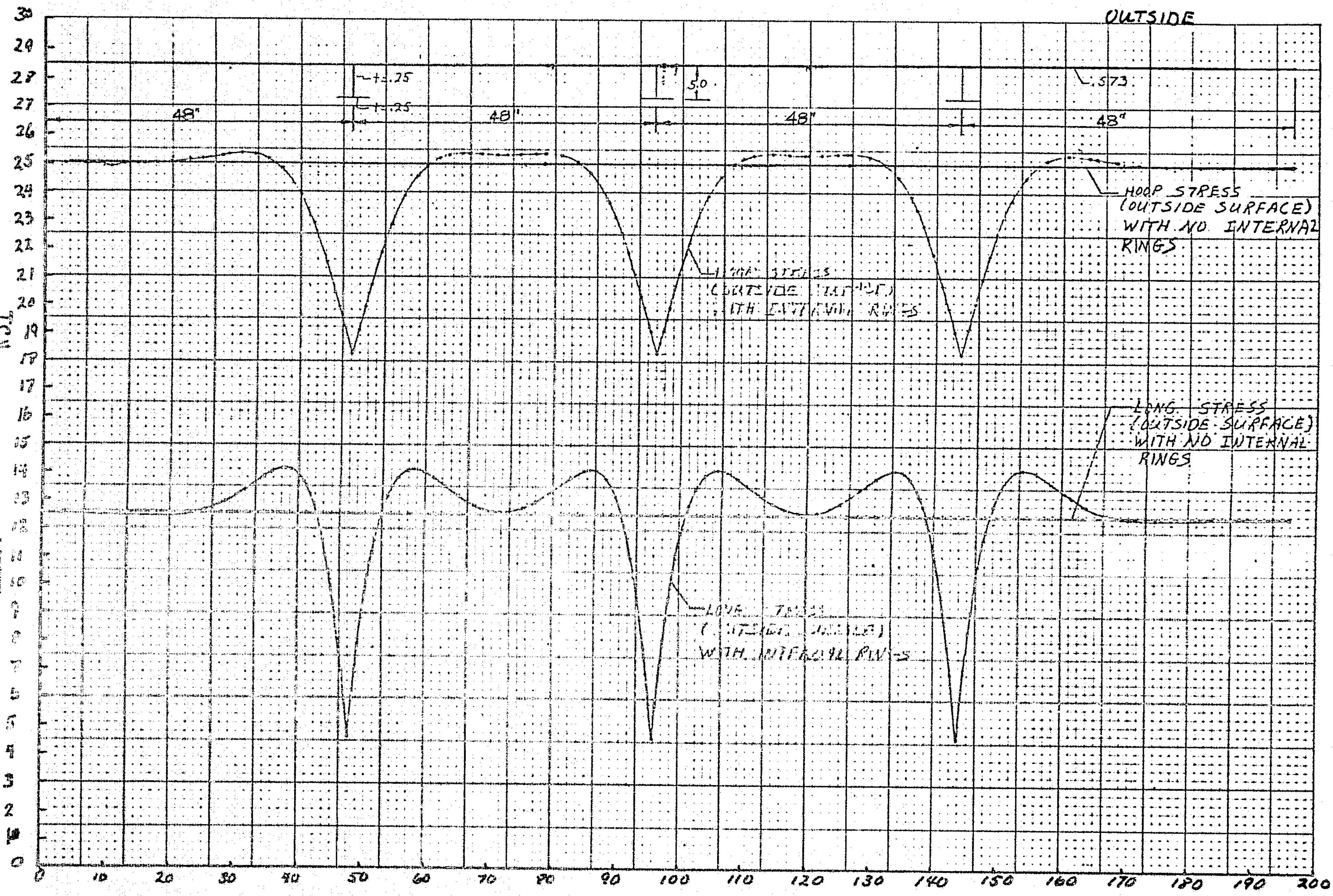
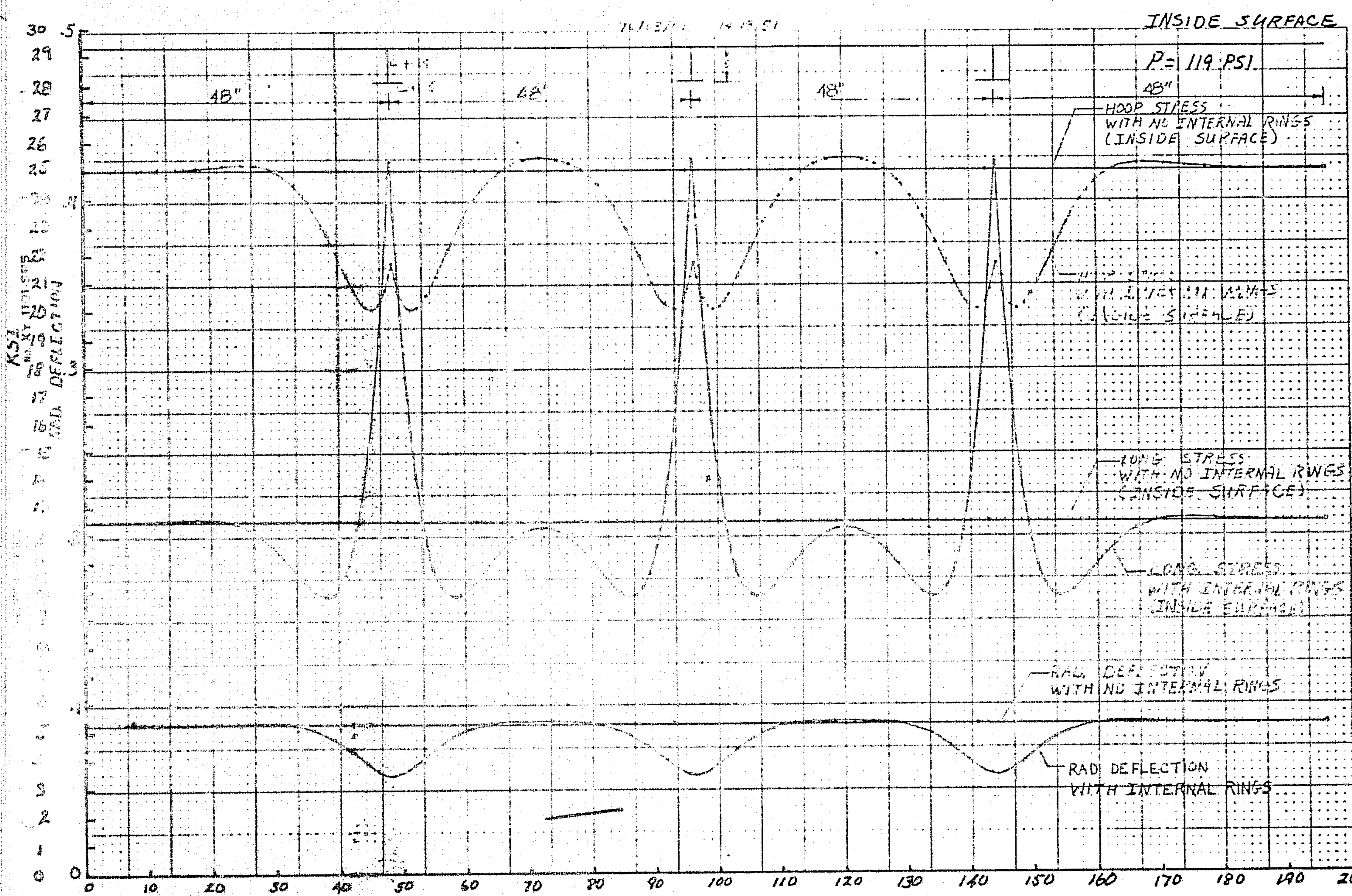


Fig 3

...DUCIBILITY OF THE
...AL PAGE IS POOR



INSIDE SURFACE
P = 119 PSI
48"
48"
48"
48"
HOOP STRESS
WITH NO INTERNAL RINGS
(INSIDE SURFACE)
LONG. STRESS
WITH NO INTERNAL RINGS
(INSIDE SURFACE)
LONG. STRESS
WITH INTERNAL RINGS
RAD. DEFLECTION
WITH NO INTERNAL RINGS
RAD. DEFLECTION
WITH INTERNAL RINGS
KSI
RAD. DEFLECTION

Fig 4